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The Institution of Electrical Engineers

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EDITED BY P. F. ROWELL, SECRETARY

SAVOY PLACE, VICTORIA EMBANKMENT, LONDON, W.C.2

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[*Continued on page (III) of Cover.*

THE JOURNAL OF
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THE REMOVAL OF SMOKE AND ACID CONSTITUENTS FROM FLUE GASES BY A NON-EFFLUENT WATER PROCESS.*

By J. L. PEARSON, B.A., Ph.D., G. NONHEBEL, B.A., B.Sc., and P. H. N. ULANDER.

(*Paper first received 22nd November, 1934, and in final form 4th April, 1935; read before a Joint Meeting of* THE INSTITUTION *and* THE INSTITUTE OF FUEL *17th January, also before the* NORTH-EASTERN CENTRE *28th January, and before the* NORTH MIDLAND CENTRE *19th February, 1935.*)

Section I.—INTRODUCTORY AND GENERAL.

A. THE TREND OF MODERN REQUIREMENTS IN FLUE-GAS CLEANING.

Progress in the electricity supply industry has led to a large increase in the coal consumption of individual power stations and is leading to the erection of power stations consuming over 1 000 tons of coal per day.

This concentration of coal consumption in a small area has greatly intensified certain aspects of atmospheric pollution, owing to the creation of "point" sources of very substantial emission, i.e. sources of an order of emission unknown some 25 to 30 years ago. The almost immediate effect of the developments in power station "size" has been to bring the 600-year-old question of atmospheric pollution to a stage insistent upon practical solution, for the consumption of 1 000 tons of average coal leads to the formation and emission of 45 tons of sulphuric acid, 3 to 7 tons of nitric acid and half a ton of hydrochloric acid, as well as to substantial amounts of dust.

Three new power stations, Battersea, Swansea, and Fulham, indicate clearly the trend of flue-gas cleaning requirements in urban areas. In the past, manufacturers of flue-gas cleaning apparatus have devoted their activities, mainly to the removal of grit, partly to the removal of dust, and not at all to the removal of the acid constituents in the gas emission. This is well illustrated in Table 1, where under the second column of "Percentage removal" it will be seen that the performance of standard flue-gas cleaning apparatus in removing the acid constituents is negligible, except for the developments in new apparatus referred to at the end of the table.

It should be noted that the figures represent stated performances of plants and that the methods of testing were probably different in most cases and of unknown accuracy—except for the two cases at the end of the table. The table is mostly compiled from information given in the 1932 Report of the Committee appointed by the Electricity Commissioners† and in a report of the Prime Movers Committee of the U.S.A.‡

B. CLASSIFICATION OF OBJECTIONABLE CONSTITUENTS IN FLUE-GAS EMISSION.

The objectionable constituents in flue-gas emission can be classified logically in accordance with the process of their distribution after emission, for average wind conditions, as:—

(1) *Grit.*—Solid particles of such size and density that the settlement rate is the major factor in determining the horizontal distance of travel and in fixing the concentration distribution in the air. In general the size is 35 microns upwards. Commercial plant for the prevention of emission is available and well known, but in the past plant for the removal of grit has not dealt materially with "dust" and "acid gases."

(2) *Dust.*—Solid particles from 35 microns downwards, constituting usually 70 per cent or more of the solids in flue gases. After emission the particles are distributed by eddy diffusion and follow approximately or completely the concentration distribution normally associated with gases. Like the acid gases they are brought down by rain, but to a greater extent. The number of particles below 20 microns is enormous, and

* Condensed form of a paper which was read before the Institution and the North-Eastern and North Midland Centres. The full paper has been published in the *Journal of the Institute of Fuel* (1935, vol. 8, p. 119).

† See Reference (1).

‡ *Ibid.*, (2).

they are factors in the curtailing of sunlight and in the production of haze, fog, and gloom generally, in the large urban areas.

(3) *Acid Gases.*—Oxides of sulphur, oxides of nitrogen, and hydrochloric acid. Their concentration distribution in the air after emission is governed by eddy diffusion. Any successful wet process for the effective elimination of these would be a *complete* solution, since it would also eliminate grit and dust. CO_2 is not included as an acid gas here, because:—

(*a*) The concentration distribution after emission with a reasonable height of chimney is such that the amount present under average conditions is innocuous.

(*b*) Its low solubility in water prevents much more than the normal amount being brought down by rain.

(*c*) It does not contribute to the production of haze or fog.

C. The Distribution of Acid and Dust Emission from a Point Source.

The distribution of "acid" and "dust" constituents in flue-gas emissions is dealt with more fully in Section II of the edition of this paper as published in the *Journal of the Institute of Fuel.** The more detailed treatment there is based upon data from well-observed phenomena such as the spread of cigarette smoke in a moderately draughty room, the drift of smoke from domestic and industrial chimneys, the drift of small balloons and water spray, and the diffusion of odours, as from a domestic chimney "on fire."

It is a matter of common observation *that the temperature of the flue gas has practically no effect at all* on the spread of the smoke from an industrial chimney, as long as there is any appreciable wind (i.e. a wind, say, over 2 metres per sec., or 4·5 miles per hour, or for well over

* See Reference (3).

Table 1.

Performance of Flue-Gas Cleaning Equipment on Pulverized-fuel Boilers.

Type of plant	Location	Percentage removal: Dust	Percentage removal: Sulphur
Dry Cyclone:			
Davidson cyclone	Germany	60–72	Nil
Static centrifuge	Vitry, Paris	65	Nil
Centrifugal blower	—	50	Nil
Centre vane fan and cyclone	Hardecke, Ruhr	60–70	Nil
Cyclone	Mannheim	75	Nil
Cyclone	Duisberg copper smelting works	52–59	Nil
Centrifugal collector	Derby	50	Nil
Wetted Cyclone:			
Cyclone with wetted rubber-covered vanes	I.G. Works, Oppau and Ludwigshafen	91	20
Cyclone followed by Sprays	Duisberg copper smelting works	92–93	Not stated
Electrostatic:			
Make not stated	Vitry, Paris	75	Nil
Make not stated	Klingenberg, Berlin	95	Nil
Make not stated	I.G. Leuna Works, Merseberg	95–98	Nil
Make not stated	Trenton Channel, U.S.A.	78	Nil
Make not stated	Leipzig Nord power station	97	Nil
Lodge-Cottrell (including soot-blowing)	N. Met. E.S. Co., Willesden	75	Nil
Lodge-Cottrell (excluding soot-blowing)	N. Met. E.S. Co., Willesden	81	Nil
Sturtevant	N. Met. E.S. Co., Brimsdown	88–91	Nil
Siemens-Schuckert	Gartenfeld cable works, Germany	80	Nil
Wet washers:			
Modave	Vitry, Paris	90–95	18
Modave	Billingham	95	25–30
U.S. Co. spray and baffles	Derby	94	30–52
Tower packed with hurdles	Producer-gas cleaner in U.S.A.	99	Not stated
Howden–I.C.I. experimental corrugated plate deduster	Brimsdown	—	70
Battersea power station (Sprays and packing) (With final alkaline wash)	Stoker-fired boilers, plant designed to remove as much SO_2 as practicable	Not stated	90
Howden–I.C.I. experimental grid-packed scrubber	—	98	98

90 per cent of the time). This can be verified easily by anyone. Such wholesale swamping of what should lead to considerable vertical convection currents was, some 50 years ago, an apparent paradox and led to the first investigations on eddy diffusion. These investigations have provided a full explanation, as far as practical purposes can be served, of the spread of smoke, acid gases, and dust, in the open air, in all cases where the wind velocity exceeds 2 metres per sec. They also form the basis of Fig. 1, which is constructed from curves giving a close approximation to all accredited observations on the subject.*

The process of eddy diffusion can be actually seen by watching the drift of smoke from a chimney under normal wind conditions, the eddy diffusion being visible in the changing contortions and convolutions of the smoke ribbon. A single photograph illustrates the mechanism of spread; a composite photograph, made from the superimposition of several photographs taken at intervals of, say, 15 to 30 seconds, shows the spread of the visible cone of discharge. Outside that cone there is invisible spread, whilst with increasing distance from the chimney the spreading cloud becomes more and more attenuated and then invisible, but the pollution is still there.

For general purposes, and up to a distance of between 1 and 2 miles, no great error will be made if the dust and acid pollution is taken as spreading on the windward side of the source of emission as a cone with a solid angle of 20°, the concentration at the edges of any cross-section being one-tenth of that at the axis, and the concentration at the axis diminishing downwind, varying inversely as the square of the distance, inversely as the wind velocity, and directly as the mass rate of emission of the pollution. Such a cone will include about 90 per cent of the pollution emitted. The practical result of interposing the ground, as a plane parallel to the axis of the smoke drift, is to double the concentration of "the freely developing cloud form" at ground level.

The above approximate method of treating pollution emission from point sources enables the problem of high chimneys to be dealt with in a simple manner, especially if it is remembered that the worst ground concentration occurs at about 8 chimney heights away from the chimney base.

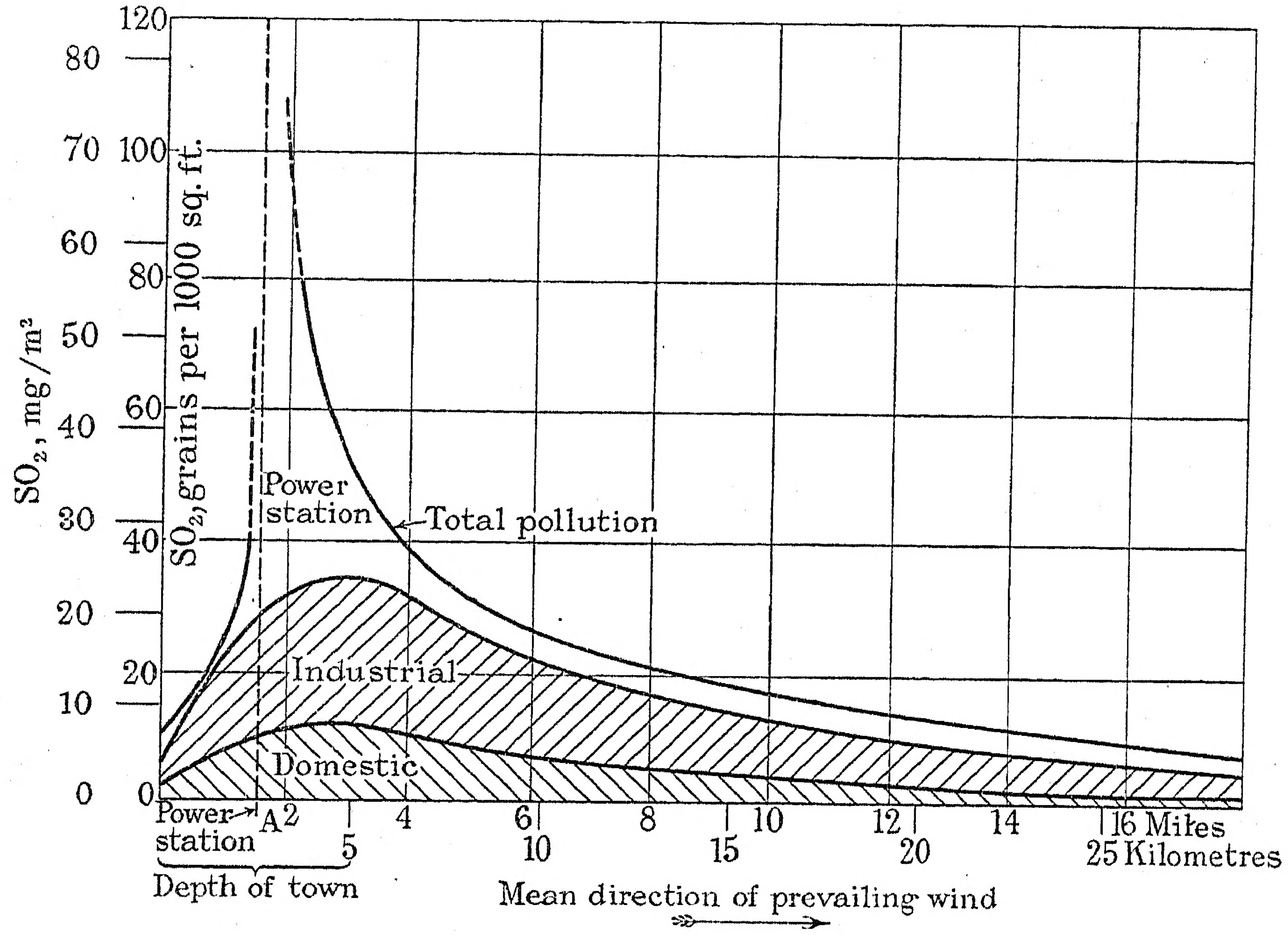


FIG. 1.—Mass-over-area distribution of SO_2 as averaged over the year in urban areas. The diagram shows the integrated density in mg SO_2 per m² for an industrial town of 5 km square burning 3 750 tons per day of coal containing 1 per cent of sulphur with a power station located at its centre burning 1 000 tons per day of similar coal. The curves give average values for the SO_2 over the axis of the power station smoke cloud in the direction of the prevailing wind, the rate of which is assumed to be 5 m per sec.

* See Reference (3), Appendix II.

D. THE PROBLEM OF HIGH CHIMNEYS.

Atmospheric pollution must be considered under two types of weather conditions, viz.:—

(i) Normal weather conditions when the wind velocity is above, say, $2\frac{1}{2}$ metres per sec. (It would be truer to use a limit of 2 metres per sec., but $2\frac{1}{2}$ metres per sec. simplifies the calculations—the average wind in Great Britain being 5 metres per sec.—and will introduce no appreciable errors.)

(ii) Abnormal weather conditions when the wind velocity is below $2\frac{1}{2}$ metres per sec. (as usually accompanying temperature inversions, when hazes and fogs occur).

For each of these types three aspects must be taken into account, viz. the effects produced from

(*a*) the vertical concentration and depth of the pollu-

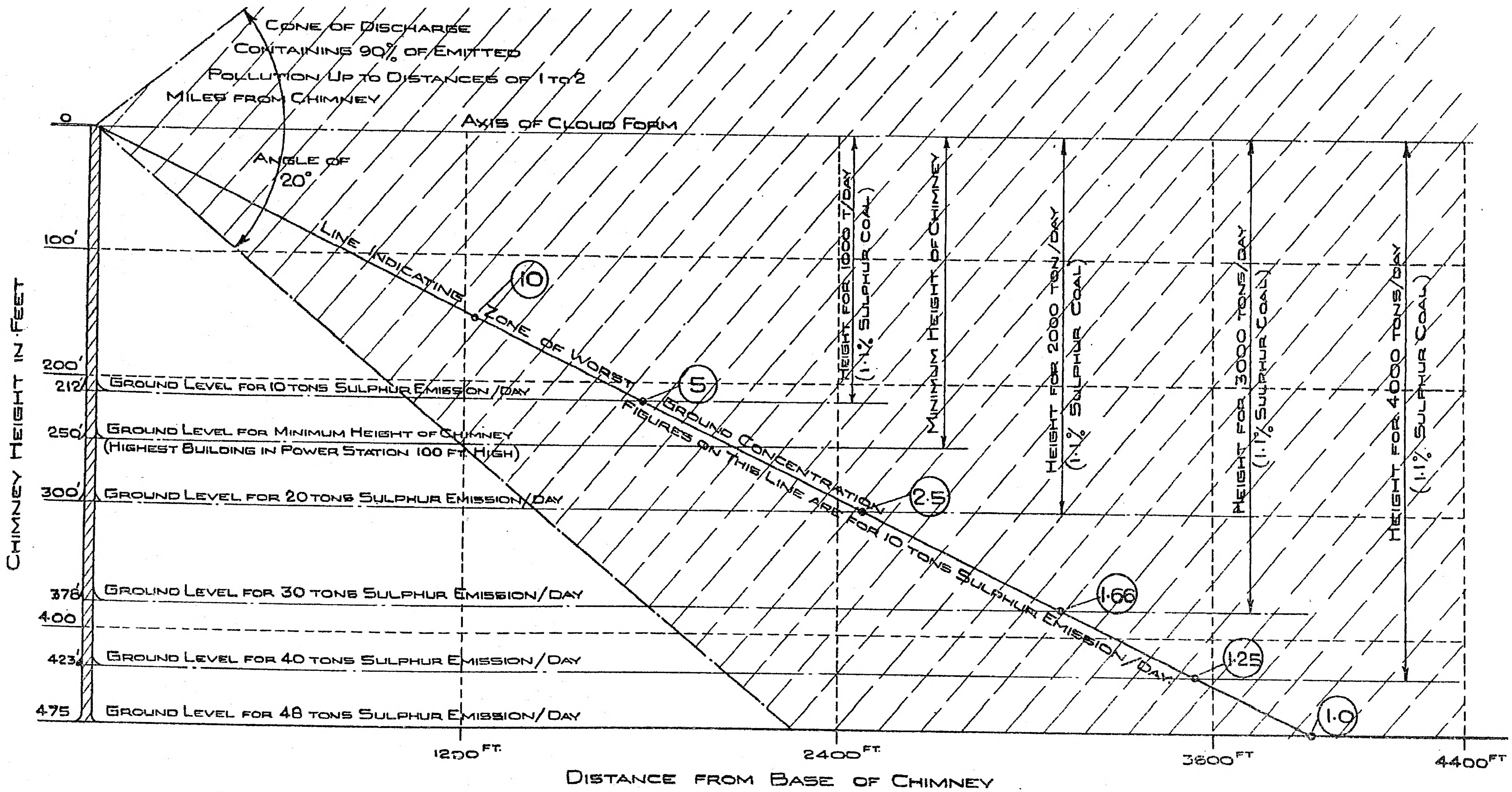


Fig. 2.—Reasonable chimney height as determined by mass rate of emission of sulphur per day in order to give a worst ground concentration of not more than 5 mg SO_2 per m^3 with an assumed wind velocity of 2·5 m per sec. and with no sulphur-extraction plants. (Note.—Figures in circles are mg SO_2 per m^3 when emission is 10 tons of sulphur per day. Horizontal scale is $\frac{1}{4}$ of vertical scale. All ground levels are for worst ground concentration of 5 mg SO_2 per m^3.)

tion when it is raining (as affecting buildings and vegetation),

(*b*) the vertical concentration and depth of the pollution when it is not raining (as affecting the curtailment in sunlight and ultra-violet rays transmitted),

(*c*) the worst ground concentration.

Clearly chimney height cannot affect considerations under (*a*) and (*b*) under either normal or abnormal weather conditions. It can hardly affect (*c*) under abnormal weather conditions, since temperature inversions* extend to such a height and have such a depth of deck (through which diffusion upwards does not take place) that in general no practicable chimney height would pass through the deck. It can, in practice, only affect (*c*) under normal weather conditions, i.e. it can only affect the virtually least important of the six aspects mentioned, since already chimneys have to be built to such a height as to render the worst ground concentrations tolerable.

Chimney height, in urban areas, must be at least such that the flue gases are not brought down directly, on emission, by down draughts. This fixes the minimum chimney height at about 250 ft. (dependent on the height of the nearest buildings, or, say, $2\frac{1}{2}$ times that height).

The only other consideration generally obtaining at present with regard to chimney height is that the worst ground concentration of sulphur, as SO_2, should not under normal weather conditions be noticeable by smell and should not be appreciably inimical to health. This unfortunate maximum percentage as tolerated to-day has never been precisely laid down, but if we take a figure of 5 mg SO_2 per m^3 ($1\cdot9$ vols. SO_2 per 10^6 vols. air) *as calculated from the mass rate of sulphur emission*, we shall not be far out for practical purposes. Then under normal weather conditions, assuming a wind velocity of $2\frac{1}{2}$ metres per sec., and a chimney height of 250 ft., the maximum mass rate of sulphur emission, in order not to exceed the figure just given for the worst ground concentration, will be 12 tons of sulphur per day, or the equivalent of 36 tons H_2SO_4 per day. Most of the power stations in Great Britain are below this figure for mass rate of sulphur per day, but in future many will exceed it.

Above the mass rate of emission of 12 tons of sulphur per day, chimney height must be increased above 250 ft., the height being directly proportional to the square root of the mass rate of emission in order not to exceed the maximum ground concentration given above (that is, of course, unless complete flue-gas cleaning is adopted). This is quite simply illustrated in Fig. 2.

In Germany there are a number of power stations emitting pollution at the rate of about 48 tons of sulphur per day. This means that the chimneys must be 500 ft. high, if ground concentrations usual to-day in Great Britain and elsewhere are not to be exceeded and if the local inhabitants are not to be vigorously gassed. Such high chimneys are, in the circumstances, clearly compulsory and do not improve conditions from the other five aspects given under (*a*), (*b*), and (*c*), and (i) and (ii) above, these conditions getting worse proportionately to the mass rate of emission and not being affected by chimney height.

* See Reference (4).

E. The Requirements in Flue-gas Cleaning in Urban Areas as fixed from Considerations of Emission Distribution.

It should be noted in connection with Fig. 1 that:—

(*a*) Under temperature-inversion conditions the SO_2 mass distributions (and the dust distributions which can be similarly obtained) are considerably increased, in some cases by as much as 10 times.

(*b*) *Average* conditions throughout the year are represented and that for short specific periods of time (say of several days), when the wind swing is only, say, $4\frac{1}{2}°$ each side of the mean direction, the power station pollution would be multiplied by 10, and the general industrial and domestic pollution as line sources by 2 (the latter being almost unaffected by wind swing).

Examination and correlation of distribution data for "dust" and "acids" reveal the logical lines along which remedies should be sought and the extent to which they should be applied in urban areas. The general conclusions are:—

(1) In general, the problem of flue-gas emission is confined to large urban districts, where there is a combination of maximum pollution and maximum incidence of pollution.

(2) Whilst the presence of grit in flue-gas emission has been generally recognized as being objectionable, the damage to property and health arising from flue-gas emission in urban areas results mainly from the acid and dust constituents on account of their nature, and of their distribution after emission.

(3) Remedies should be sought in an ordered sequence, as indicated by the mass-over-area distribution curves for urban districts. This sequence agrees also with the progressive increase in practical difficulty to be expected in applying a cure to the different types of emission. The sequence is:—

First.—Power-station emission.
Second.—General industrial emission.
(Priority in each of these two types to be governed by local conditions and mass emission.)
Third.—Domestic emission.
(A process of slow elimination is already in being.)

In practice, cases of mass emission in the second type, of an order characteristic of the first, should be included under power-station emission.

(4) Dust and acid constituents should be removed from power-station emission in urban areas, to the maximum extent now practicable (as exemplified by the mass-over-area distribution curves) as long as the other two types of emission still persist—irrespective of any distorted outlook on "apparent" cost. (Afterwards a higher standard may be demanded.)

(5) Increase in chimney height may be useful for spraying grit over a wider area, but it is useless as a remedy against "acid" and "dust" emission. Chimney height should be reasonable, but need not be excessive except when inefficient apparatus for grit removal only is installed.

(Note.—The distinction between grit and dust is based upon settling rate versus diffusing rate. The line of demarcation is about 35 microns for average

conditions, 10 microns or less (according to size of town) for urban fog conditions, and 60 to 70 microns for ordinary strong winds of 30 to 40 miles per hour. Grit settles, whilst dust diffuses laterally, and vertically upwards and downwards.)

These conclusions, based upon the fundamental principles underlying pollution diffusion in the atmosphere, definitely delineate, in conjunction with present technical knowledge, the system of flue-gas cleaning likely to be demanded and to be acceptable for general application to the power stations in urban areas. High extraction efficiencies for the acids, dust, and grit, in the flue-gas emission are called for, and the only system capable of satisfying such requirements is a wet washing system.

F. The Universality of a Non-effluent Cleaning System.

Considerable restrictions already exist with regard to the pollution of streams near urban areas, and existing restrictions are likely to become more drastic and more extended. It is therefore, in general, useless to solve the problem of atmospheric pollution at the expense of river pollution. Modern conditions demand a wet washing system to give the extent of the cleaning of the flue gases required, and a non-effluent liquor system to meet restrictions on effluent disposal to water courses. (The system, however, should be adaptable to an effluent cycle for those relatively few cases where effluent washing may be permissible.)

In such a system the acid constituents of the flue gases must be fixed and removed from the system as solids. This means the addition, to the circulating liquor, of the cheapest form of alkali available, i.e. of CaO in the form of lime or chalk, both of these being available in quantity practically everywhere.

The universally acceptable system of flue-gas cleaning is illustrated simply in Fig. 3, where is shown the natural division of the plant into three sections—lime mixing, scrubbing, and solids separation—together with the main interconnections.

The materials "in" and "out" of the complete plant are "in," lime and a relatively small quantity of water, "out," wet solids, i.e. grit, dust, calcium sulphite, and calcium sulphate.

An examination of this diagram reveals that the process will include types of apparatus used quite commonly in the chemical industry, that no great trouble is to be anticipated with developing or working modifications of existing standard apparatus included under the lime section and the "solids" separation section, and that the only serious difficulties to be expected in developing the process will lie in the scrubbing section, where:—

(i) The initially low concentrations of SO_2 in the flue gases are not immediately suggestive of relatively small and compact plant, unless more effective absorbing surfaces than those in common use are utilized.

(ii) Reasonably small dimensions of the "solids" separation section will require the handling of a relatively small bleed from the main re-circulating system, which should, therefore, be normally run with a substantial amount of solids in suspension, and yet, as first indicated, highly efficient absorbing surfaces should be incorporated in the scrubbing sections.

(iii) Continuous absorption of SO_2 in lime-treated and re-circulated aqueous media will result in the formation of calcium salts which readily precipitate from saturated solutions as scale or growths on the absorbing surfaces, unless means can be found to combat successfully this tendency and/or to control saturation or supersaturation.

(iv) The perfect functioning of the process will require the development of some recording instrument, from which the lime slurry addition to the main circulating system can be easily and accurately controlled as the load varies.

The first two of these will largely determine the nature

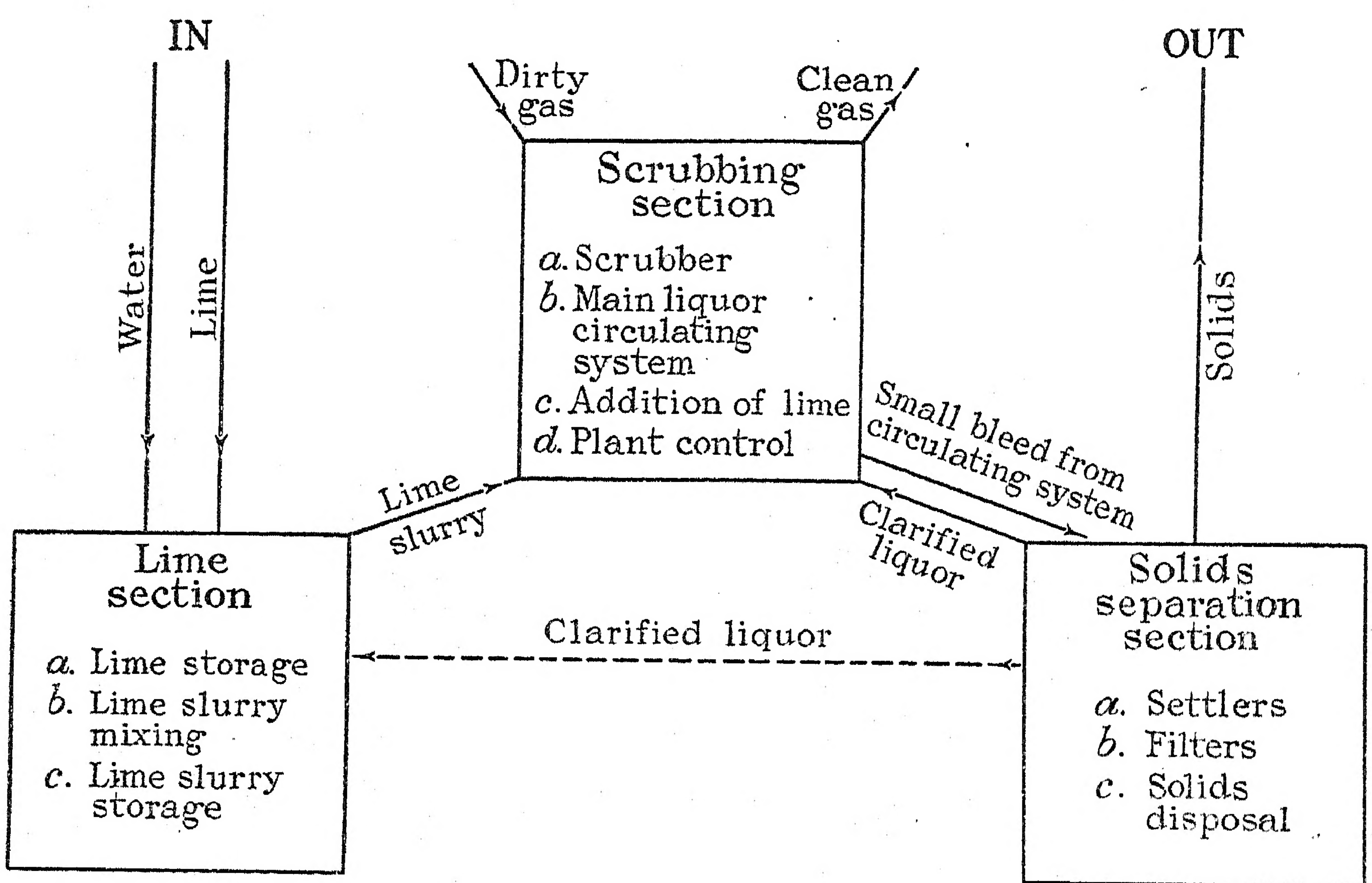


Fig. 3.—Simple diagrammatic representation of the three sections comprising a non-effluent lime-treated flue-gas scrubbing plant.

of the absorbing surfaces. The third will fix any necessary treatment of the main body of re-circulating liquor, and may to some extent react on the scrubbing surfaces, while the fourth will influence simplicity in plant control.

Such, then, was the general basis from which the authors' investigations on the complete cleaning of flue gases began, and which led to the development of a successful process.

Section II.—THE PRINCIPAL FACTORS IN THE DESIGN OF THE SCRUBBING SECTION OF THE HOWDEN–I.C.I. NON-EFFLUENT WATER SYSTEM FOR FLUE GAS CLEANING.

A. The Major Problems Encountered in Developing a Non-effluent Process.

The remainder of this paper is devoted to describing a new plant and a new process developed for the simultaneous removal of grit, dust, and oxides of sulphur, from flue gases, in which the removal is effected in an efficient and compact scrubber using a re-circulating aqueous medium, treated with lime or chalk. The process employed is different from others, inasmuch as complete flue-gas cleaning takes place in the simple form of scrubber incorporated, and it has the two further novel features that:—

(*a*) For the first time in flue-gas cleaning a really efficient scrubber, based on fundamental principles, has been employed; and

(*b*) No liquor need be put to drain, consequently large supplies of water are not required and the possibility of river pollution is completely avoided.

The major problems encountered during the development of the process were found to be generally along the lines indicated at the end of Section I (F), although certain special circumstances (to be described) removed most of the difficulties which would normally have been associated with the development of satisfactory scrubbing surfaces suitable for the requirements of the process involved.

The major problems may be summarized as follows:—

(1) *Absorption Surfaces.*—The choice and design of a non-choking scrubber packing, with high absorption characteristics, capable of taking large liquor rates without cascading or flooding, with a suitable scaling resistance and with an optimum incidence on capital and running charges when operating with very high extraction efficiencies for dust and SO_2 removal.

(2) *Circulating Liquor Treatment.*—The determination of ways and means whereby—

(*a*) outside the scrubber—supersaturation of the circulating liquor with calcium sulphite and sulphate could be either completely or substantially destroyed; and

(*b*) inside the scrubber—the scaling potential arising from slight supersaturation of the circulating liquor with calcium sulphite or calcium sulphate could be controlled and maintained below the higher limit, at which it cannot overcome the scaling resistance of the packing chosen.

(3) *Plant Control.*—The development of a pH recorder, operated from the power mains, having a degree of sensitivity consistent with close plant control, having a degree of reliability better than, or equal to, most of the instruments normally installed on boiler plants, and having technical characteristics not beyond the ready comprehension of the average boiler plant engineer.

The "liquor treatment" side was by no means easy of solution, and most of the investigational work and pilot-plant running was devoted to this side, which was found to react in some measure on the problems relating to absorption surfaces and plant control. It was found that the question of liquor treatment, with a view to preventing completely scale formation on the scrubbing surfaces, constituted the most difficult aspect in evolving a satisfactory non-effluent system. This will readily be understood after considering the fundamental chemical reactions occurring in a lime-treated, non-effluent system, with simple re-circulation, but with the necessary "bleed" to remove the make of solids and with return of the clarified liquor from this bleed.

B. The Fundamental Chemical Reactions Occurring in a Simple, Lime-treated, Non-effluent Water Process.

The flue gases entering a scrubbing plant may contain:—

Grit and dust ..	0·5 to 7 grains per cub. ft. at N.T.P.
CO_2	10 to 14 per cent by volume.
O_2	9 to 4 per cent by volume.
SO_2	0·05 to 0·20 per cent. (or 0·3 to 1·1 grains sulphur per cub. ft. at N.T.P.)
SO_3	Traces, up to 10 per cent of weight of SO_2.
HCl	Traces, of the order of 0·05 grain HCl per cub. ft.
NO and NO_2 ..	Traces, of the order of 0·05 grain combined nitrogen per cub. ft.
H_2O	Corresponding to partial pressures of 0·05 to 0·08 atmosphere.

To obtain complete, or substantially complete, absorption of the SO_2 and other acid gases with a closed re-circulating water system, it is necessary to add an alkali. Lime or reactive powdered chalk are the cheapest alkalis, and are added in the form of a slurry.

If lime is added to water used in washing flue gases, it rapidly combines with the CO_2 dissolved in the water to produce:—

(*a*) chalk ($CaCO_3$), which is insoluble, and

(*b*) calcium bicarbonate, [$Ca(HCO_3)_2$], which is soluble.

Addition of chalk direct will also result in the formation of calcium bicarbonate. It is the dissolved calcium bicarbonate which is the active absorptive agent for the acid constituents in the flue gases. Fresh calcium bicarbonate is continuously formed from the chalk (whether chalk or lime is added), as absorption and neutralization of the acid constituents in the flue gases proceed.

When lime or reactive powered chalk are added continuously to the circulating liquor at a rate equivalent to that of acid absorption, the pH of the liquor falls from

a pH between 6·5 and 6·8 at the liquor inlet to the scrubber to a pH between 6·0 and 6·2 at the liquor exit.*

The SO_2 and SO_3 are absorbed from the flue gases as calcium sulphite and calcium sulphate respectively, and since none of the re-circulating water is put directly to drain, the liquor in the system is saturated with these relatively insoluble compounds. The two salts $CaSO_3 . 2H_2O$ and $CaSO_4 . 2H_2O$—calcium sulphite dihydrate and calcium sulphate dihydrate (gypsum) respectively—are precipitated. The other reaction products, such as calcium chloride and calcium nitrite, are highly soluble, and owing to the slight water loss from the system (with the solids), and the resulting slight water make-up, they do not reach saturation in the circulating liquor or solution. It should be noted here that the solubility of calcium sulphite increases with fall in pH, and that consequently the liquor leaving the scrubber can hold more of this salt in solution than that entering the scrubber.

Since, in solution, calcium sulphite is readily oxidized to calcium sulphate, a substantial part of the calcium sulphite produced in the plant is oxidized, partly in the scrubber (for the flue gases contain oxygen), and partly in the circulating system outside the scrubber. This oxidation is catalysed by traces of iron and manganese salts. Both of these are present in the ash from the coal and in the lime added, and pass in part into solution in the circulating liquor. The nitrites present may also oxidize part of the calcium sulphite.

As a result of oxidation, the sulphur absorbed as SO_2 and SO_3 from the flue gas appears in the precipitated solids or mud of the circulating liquor as a mixture of calcium sulphite and sulphate (30 to 80 per cent of the total sulphur as $CaSO_4 . 2H_2O$, and 70 to 20 per cent as $CaSO_3 . 2H_2O$, according to the oxidizing and catalysing agents present).

The flue gases, in passing through the scrubber, come into thermal equilibrium with the circulating liquor, are cooled to their " wet bulb " temperature, and leave the scrubber saturated with water vapour. Some loss of water thus results from the evaporation necessary to effect such saturation. In addition, water is lost from the system through being entrained or chemically combined with the solids—(ash, $CaSO_3 . 2H_2O$, $CaSO_4 . 2H_2O$)—which are discarded after separation. The water make-up required to compensate for these losses is relatively small, and amounts to slightly over half a ton of water per ton of coal fired.

As summarizing the above reactions, it can be stated that in a simple lime-treated non-effluent water process the flue gases are washed with a water containing—

(a) *In suspension*: ash, chalk, calcium sulphate and calcium sulphite;

(b) *In solution at or above saturation*: calcium sulphate and calcium sulphite;

(c) *In solution not at saturation*: calcium bicarbonate, calcium chloride, calcium nitrite, etc., and accumulations of salts remaining from the continuous evaporation of water.

Due to the presence of dissolved CO_2, the circulating water is slightly below the neutral point when it enters the scrubber, but the fall in pH within the scrubber is small, as the chalk in suspension dissolves in the CO_2 solution to replace the bicarbonate neutralized by the acid constituents absorbed from the flue gases.

The implications of (b) above epitomize the difficulties in evolving a satisfactory non-effluent process. The simple re-circulating system just described would choke up very rapidly.

C. The Problem of Liquor Treatment as Directed to the Prevention of Scaling.

In the general case of absorption of an " acid " gas by means of a re-circulated liquor carrying the necessary " base," the " base " content being maintained constant by continuous addition, the salt or salts formed in solution will precipitate out as crystals when the circulating liquor has attained a certain concentration as a solution of the salts concerned. The make of precipitated solids per liquor cycle will then be equivalent to the " acid " absorption per cycle.

With certain salts, precipitation from solution in this way would occur at saturation. The circulating liquor would continue to run at saturation, the rate of make of salt in solution being also the rate of make of salt precipitated. In most of these cases, precipitation of the salt would occur not only on the crystals carried by the liquor in suspension, but also on the absorbing surfaces, which would, sooner or later, become covered with scale and, eventually, choked up completely.

To obviate such an occurrence, when working with salts which deposit from saturated solutions, would require the arranging of a liquor cycle, in which the liquor during its passage through the scrubber was not saturated. This could be done in many cases by utilizing the change in " salt " solubility, usually accompanying change in temperature, and could be effected by:—

(a) Cooling the liquor, after leaving the scrubber, to a temperature below the saturation temperature as fixed by the amount of salt in solution;

(b) Thereby precipitating the salt as a solid, in an amount equal to the make in solution per cycle;

(c) Heating the liquor before return to the scrubber.

The thermal cycle outside the scrubber would be operated on a temperature range sufficient to avoid saturation in the scrubber in relation to the absorption and rate of make involved, and would thus prevent scaling by providing for absorption and salt formation in solution within the scrubber, and for salt precipitation outside the scrubber.

Calcium sulphite and sulphate do not lend themselves

* Since the term pH occurs frequently in this paper, and its exact connotation may be unknown to those readers who are not chemists, pH can be briefly explained as being a measurement expressing small concentrations of acidity or alkalinity. It is expressed as a number.

The following shows how the accepted method of expression of pH varies as a change is made from acid to alkali:—

		pH
Acid	Solution of 0·05 per cent sulphuric acid in water	2
	Pure water in contact with air containing normal proportions of CO_2	5·5–6·0
Neutral—	Absolutely pure water, i.e. conductivity water	7·0
Alkaline	Tap water	7·5
	Solution of chalk in pure water	8·5
	Solution of 0·04 per cent caustic soda in water	12·0

In practice, a neutral solution, i.e. one which is neither very slightly acid nor very slightly alkaline, may be regarded as one having a pH of between 6·5 and 7·0.

to a thermal cycle, because their solubility-changes with temperature are relatively quite small. These salts, however, do possess a property which gives a complete solution to scale prevention, if the fullest possible advantage is taken of it. This property is that of forming, very readily, stable supersaturated solutions—with the corollary that precipitation takes place very slowly from solutions which are only slightly above saturation.

Considering, then, a simple re-circulating washing cycle for flue gases, using lime-treated water, the rate of precipitation per cycle of the calcium sulphite and sulphate formed would be equivalent to the rate of absorption of the SO_2 and SO_3, or the rate of make of the salts, only after the circulating liquor had attained a concentration in solution substantially in excess of saturation. The degree of supersaturation attained by the liquor would be an equilibrium figure determined by:—

(*a*) The absorption, or make, per unit volume of liquor per cycle,

(*b*) The time of the cycle.

While absorption would only take place in the scrubber, precipitation from the supersaturated liquor would take place throughout the whole of the liquor system, on the solids in suspension, on the absorbing surfaces, on the inner surfaces of the pipes and pumps, etc.

Since, however, slightly supersaturated solutions of these salts are relatively stable (i.e. stable with regard to the time period of one liquor cycle in the type of plant involved), a successful cycle should be possible by arranging for—

(i) The liquor to become but slightly supersaturated during its passage through the scrubber;

(ii) The slight supersaturation thus acquired to be destroyed by salt precipitation outside the scrubber and before the liquor returns to the scrubber.

Such a cycle can be regarded as a "time" cycle, as opposed, for instance, to a "thermal" cycle, and would clearly involve the holding up of the liquor outside the scrubber for a very considerable period compared with the time for passage through the scrubber. There would thus be outside the scrubber a very large liquor capacity in the circulating system, but it may be possible by some ascertainable method to reduce the size of this capacity.

The authors' process was developed along these lines and resulted in a plant which is completely free from scaling troubles, and which does not demand an inordinate liquor capacity outside the scrubber.

In dealing with plant liquors the presence of crystals of the salt in solution, or of isomorphous crystals, tends to prevent supersaturation. With some salts the presence of such seeding crystals completely prevents supersaturation, and their addition destroys rapidly the supersaturation in over-saturated solutions. Such salts cannot readily form supersaturated solutions of appreciable over-saturation, and the converse holds, viz. that salts readily forming supersaturated solutions of appreciable over-saturation will not have such a relatively rapid action when used as seeding crystals, in destroying supersaturation of their own solutions—or such a pronounced tendency to prevent it. They will generally have an appreciable effect, however.

Further, with salts readily forming supersaturated solutions, the de-supersaturating effects of seeding crystals increase with the proportions of seeding crystals present in suspension, the rate of increase quickly falls off, and no appreciable effect is observed on increasing the proportions of seeding crystals present beyond a certain percentage.

Dr. R. Lessing* was the first to produce accurate curves showing the rate of de-supersaturation of calcium sulphate solutions by various concentrations of suspended gypsum ($CaSO_4 . 2H_2O$), the solutions being freshly prepared laboratory solutions. His curves, shown in Fig. 4, were obtained during his investigations on flue-gas cleaning in his capacity as consulting chemist to the consulting engineers for the new Fulham power station.

As has been previously indicated, the non-effluent system to be attempted should be one in which the circulating liquor would carry substantial amounts of solids in suspension. Seeding crystals would thus be present in substantial amount.

When running with the slight supersaturation of calcium sulphate permitted in practice, the times for de-supersaturation under plant conditions are substantially greater than those indicated in Fig. 4, and the higher proportions of seeding crystals do not have such marked effect. A high concentration of suspended solids in the circulating liquor does, however, enable a substantial reduction to be made in the liquor capacity required to give the delay time necessary for removal of the slight degree of supersaturation of calcium sulphate and sulphite permitted to arise during passage through the scrubber.

Clearly, the provision of a large liquor capacity, or "liquor delay time," outside the scrubber for de-supersaturation purposes is bound up with the liquor circulating rate required to give the permitted slight degree of supersaturation within the scrubber, for the liquor, after de-supersaturation, re-enters the scrubber as a saturated solution, and during its passage through the scrubber must become at least slightly supersaturated as absorption proceeds.

Actually, in the developed process, this only applies to the calcium sulphate, for, owing to:—

(1) The increased solubility of calcium sulphite with the diminishing pH of the liquor through the scrubber (page 16),

(2) Partial oxidation *after* the pH has been restored by alkali addition,

(3) The proportioning of "make" to liquor rate,

no supersaturation at all occurs in the scrubber with regard to calcium sulphite with coals of normal sulphur content.

It will be readily understood that, from a supersaturated solution, the rate of deposition upon a non-isomorphic surface (e.g. the absorption surface) will be less than upon a surface of the same crystal form, and that the rate of deposition (or scale formation) upon the non-isomorphic surface will depend upon the degree of supersaturation actually present. These observations may perhaps be better expressed; the latter as—the scaling potential of the liquor is a function of the degree

* See Reference (5).

of supersaturation present, and the former as—non-isomorphic surfaces have a scaling resistance, or, rather, a "back-potential," against the deposition of scale.

The authors have found that the scaling resistance of an absorbing surface, or tower packing, is a function of

(*a*) The specific scaling resistance of the material of the packing (specific both for the particular material and for the particular salt);
(*b*) The initial smoothness of the surface and its subsequent behaviour under corrosion;
(*c*) The liquor velocity over the surfaces.

Thus, for example, corrosion-resistant steels and woods have a greater scaling resistance (against calcium sulphite and sulphate) than copper and brass, which are themselves better than mild steel. This last is definitely corroded at a slightly appreciable rate, and consequently initial smoothness of surface hardly affects the scaling resistance of mild steel packing at all.

In practice, these three factors can be manipulated to produce a resultant scaling resistance greater than the scaling potential, from the slight supersaturation demanded by designed conditions. Complete immunity against scaling is thus rendered possible.

It is interesting to notice that the bulk of the tower packing does not come within the practical sphere of influence of scaling potential and scaling resistance. Thus, considering counter-current scrubbing, in which the gases enter at the bottom and leave at the top, about 50 per cent of the SO_2 will be absorbed while the gases pass over the bottom 10 to 15 per cent of the packing. Above here there will be no measurable supersaturation at all, provided, of course, that the necessary "delay period" has been incorporated in the system after the scrubber. The practical effect therefore is that:—

(*a*) The greater part of the tower packing can be chosen or designed on the basis of maximum efficiency, or of non-silting characteristics, or of any other virtues desirable with an efficient packing,

(*b*) 10 to 15 per cent of the packing should be chosen or designed on the basis of maximum scaling resistance, i.e. of tolerating with impunity the small degree of supersaturation bound to occur, and this means, in practice, higher liquor velocities on the bottom packing.

(In any case, efficiency in absorbing surface is not of great moment in these bottom layers of packing, where the SO_2 concentration in the gases is relatively high.)

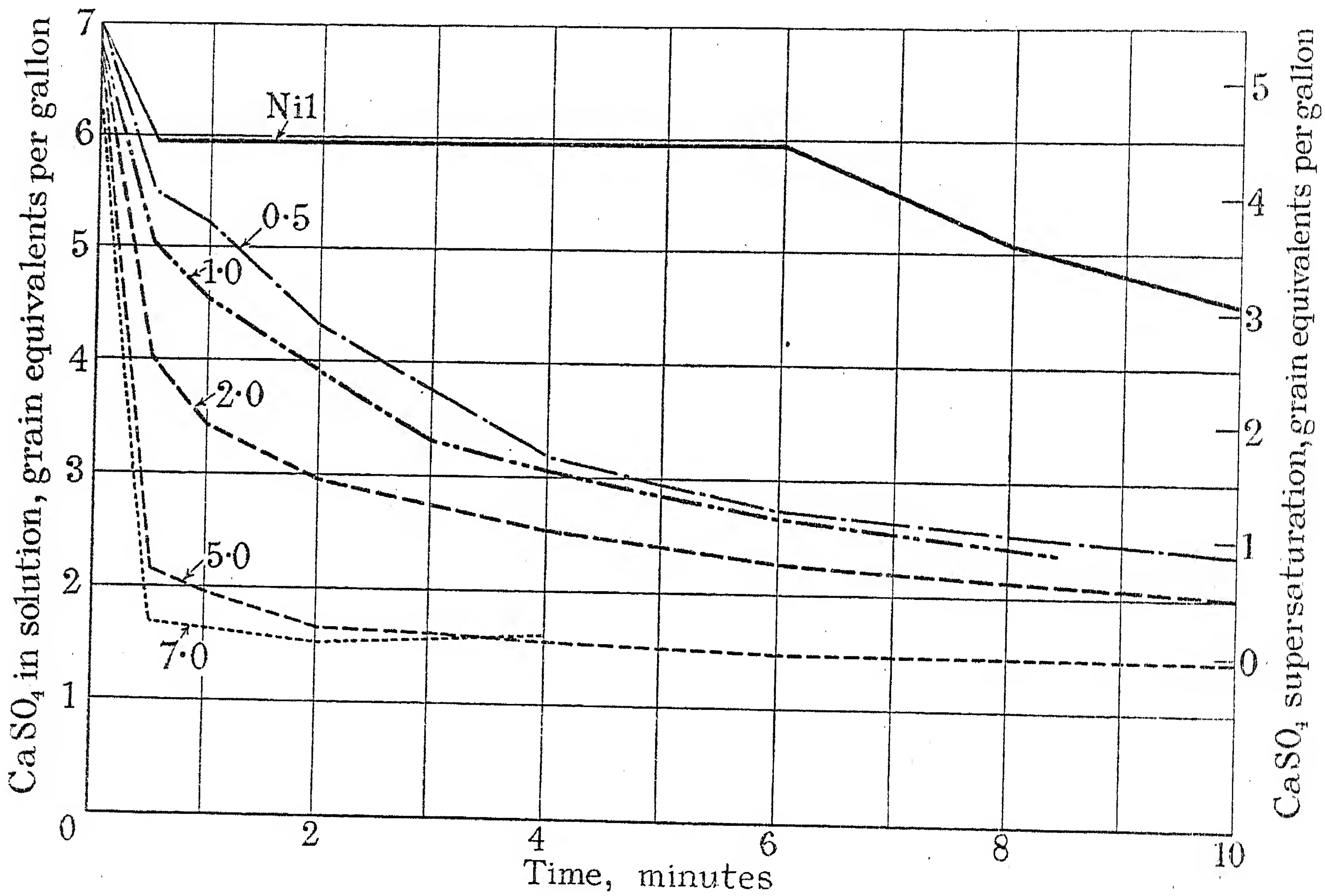


FIG. 4.—Dr. Lessing's curves showing rate of de-supersaturation of calcium sulphate solution by various concentrations of suspended $CaSO_4 . 2H_2O$.

In dealing with the question of scale prevention against calcium sulphate and, under certain conditions (high-sulphur coals), against calcium sulphite, we have still to consider how to arrange or fix the precise slight degree of supersaturation to be permitted or allowed at the bottom of the packing, and which (*a*) is to be removed by the "delay period" provided after the scrubber, and (*b*) induces in the scrubber a scaling potential *less than* the scaling resistance of the bottom section of packing.

The degree of supersaturation to be tolerated is fixed at a reasonable margin *below* that ascertained in practice as giving a scaling potential just about equal to the scaling resistance of the bottom section of packing, and productive of slow scaling over extended periods of running. From the degree thus fixed and confirmed to provide complete immunity from scaling, the capacity of the circulating liquor pumps is determined, for the

rate of sulphur extraction required is known for peak loads and the worst coals. The corresponding "delay period" is also inserted.

The permitted or "designed" degree of supersaturation cannot thus be exceeded when the plant is working, and in practice will even rarely be attained. The pilot plant has been running for many months now, with a wood packing as clean and free from scale as the proverbial "table."

D. Efficient Absorbing Surfaces.

Considering that absorption towers are as old as the chemical and certain allied industries, it is a remarkable fact that practically *all* those in use to-day are designed on "rule of thumb" and "trial and error" methods. Few people understand the mechanism of absorption, and fewer still can *design* an absorption tower with any assurance of providing for unit mass absorption at the minimum of capital and running costs. Had there been more research applied to design, there would have been less heard of "spraying" systems for flue gas cleaning.

The authors have been in the fortunate position of being able to utilize the results of work carried out over a number of years with laboratory, semi-technical, and commercial plant, on the absorption of gases in liquids, with a view to determining:—

(*a*) A useful explanation of the mechanism of this phenomenon,

(*b*) The fundamental principles enabling practical design to be based on the physical constants only of the gases and liquids concerned,

(*c*) The relative characteristics of varied types of packing,

(*d*) The import of certain practical features in design, e.g. liquor and gas distribution, liquor and gas spread after distribution, maximum and minimum irrigation rates for complete utilization of surface provided, optimum gas speeds, gas entry effects, etc.

Fundamental chemical-engineering research of this nature is essentially long-time research, and several years elapsed before the accumulating results of the research gave conclusions which could be profitably employed in practice. By the time the work on a non-effluent process for the complete washing of flue gases had begun, the fundamental relations in physical absorption had been established and "optimum" design was at last possible from the physical constants of the fluids, the characteristics of many types of packing had been ascertained and reduced to a single logical comparative basis, and the importance of certain practical features, formerly ignored or overlooked, had been proved. The work has even now not yet finished, however, for there are some apparent exceptional applications to be cleared up, and some concurrent chemical reactions to be explored.

It will be appreciated that, owing to the progress that had already been made, the design of the pilot plant for complete flue-gas cleaning presented no difficulties at all on the "absorption" side, as distinct from the "scale formation" side. Thus, for example, the pilot plant was designed for 98 per cent sulphur removal, on the basis of certain specified gas and liquor rates. It gave this performance after erection, and the original specified gas and liquor rates are those used as the basis for commercial applications of Howden-I.C.I. plants to-day.

The major requirements deciding the form of the packing originally chosen and still utilized were:—

(1) High absorption characteristics for dust and SO_2, and low costs per unit volume of scrubber.

(2) Non-silting with regard to the high solids it was anticipated would be carried in the circulating liquor of the universally acceptable non-effluent system.

(3) Capacity to take large liquor rates without cascading, and to distribute and redistribute the liquor in even irrigating films throughout the depth of packing.

(4) Low pressure-drop and high "carry-over" velocities for the gas—("carry-over" velocity is the velocity at which the gas begins to strip the liquor from the packing).

(5) Easy to make in small, readily handled units from a variety of materials such as wood, metals, and synthetic resins.

The packing chosen to satisfy these particular requirements as viewed in their correct relative perspective was a grid type packing, which gives some latitude in fixing the pitch, depth, and thickness, of the elements or strips in order to accommodate specific requirements of a particular application. Thus the grid packing selected* was composed of laths 1 in. deep, $\frac{3}{4}$ in. pitch, $\frac{3}{32}$ to $\frac{1}{8}$ in. thick, made up into grids 4 ft. square. The laths are held together every 12 to 15 in. by spacing strips, $\frac{1}{8}$ in. to $\frac{1}{4}$ in. thick, which are staggered so as to avoid division of the pile of grids into a number of small cells. The grids are piled on top of each other, the laths of one grid being at right angles to those of the one above and the one below it, and resting on those of the one below it. This latter feature ensures good liquor redistribution in films. The liquor is fed on to the top tier of grids in films by a special distributor.

With a depth of packing of 3 ft. 6 in., 98 per cent SO_2 removal was obtained using a gas velocity of 4·5 ft. per sec. N.T.P., and a liquor rate of 0·06 gallon per min. per in. of "periphery" of lath surface in one grid, i.e. per $\frac{1}{2}$ in. length of the laths in one grid (the laths, of course, having two sides). This performance is an illustration of the great advance made with respect to absorption problems by this recently developed technique.

When the pilot plant was being designed and erected it was anticipated that the major trouble, arising from carrying a large amount of solids in suspension, would occur in the liquor-distributing methods employed in the liquor distributing tank at the top of the scrubber. This proved to be the case, and, pending improvements in this direction, it was decided to run the plant as a re-circulating system with a purge to drain sufficient to give the maximum concentration of solids in the circulating liquor permitted by the liquor-distributing devices, actually in the plant for the time being. (Open Cycle—see page 18.)

In this way the plant operatives would gain valuable experience, extended runs on extraction efficiency with different materials for the grid packing would be possible, information would be gradually acquired with regard to

* It must be emphasized that each absorption problem requires a different packing for optimum performance.

scaling potential and scaling resistances, as the purge to drain was reduced and the solids in suspension built up, and the difficult question of supersaturation could be gradually approached as the conditions became increasingly difficult.

Thus it was some time before the special packing, designed for maximum scaling resistance, was incorporated in the entry gas space below the main bulk of the packing. This type of special packing as adopted carries substantial incidental advantages, as it (*a*) Gives good gas distribution, and thereby reduces the height of the tower; and (*b*) Enables 10 to 15 per cent of the shallow grid packing to be dispensed with, and effects, therefore, a further reduction in the height of the tower.

The major reason for its adoption has already been fully discussed. Summing up, therefore, we have the simple re-circulation system with minimum liquor capacity and liquor re-circulation rate, which is subject to scale,

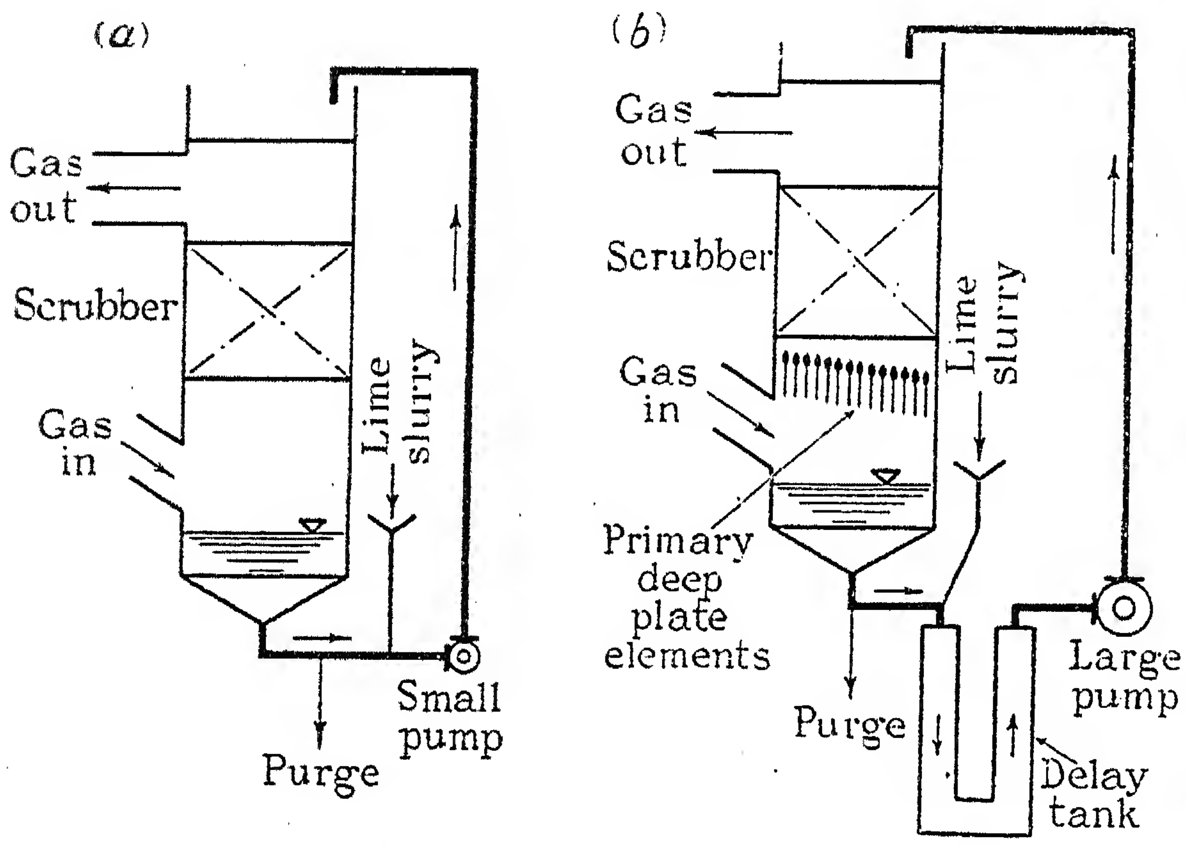


Fig. 5.—Comparison between (*a*) simple and (*b*) modified non-effluent re-circulation systems for flue-gas scrubbing by lime-treated water.

and the modified re-circulation system, free from scaling troubles, in which there are added:—

(1) Delay tank.
(2) Primary deep plate elements.
(3) Larger re-circulation pumps than are necessary for good gas absorption.

The two systems are compared in Fig. 5.

E. Plant Control.

A flue-gas scrubber may be subjected to rapidly varying loads, as firing conditions change in connection with the boiler or boilers. So far as grit and dust are concerned such changes are immaterial, but so far as SO_2 is concerned such changes are very material, since the alkali addition must keep step with the "acid" constituents absorbed, or with the "acid" constituents presented to the scrubber, if the power station is to keep within the limits of SO_2 content permitted in its emission.

Varying boiler load, and varying sulphur in the coal burnt, demand a sensitive and immediate control for the alkali added, otherwise either:—

(*a*) Extraction efficiency will diminish with impaired alkali addition, and the liquor will become corrosive, or

(*b*) Alkali will be lost with the solids if added in too great an amount with a consequent increase in running costs.

The authors have found that the pH of the liquor leaving the scrubber is constant, at $6 \cdot 2 \pm 0 \cdot 2$ when the theoretical amount of lime or chalk is added continuously

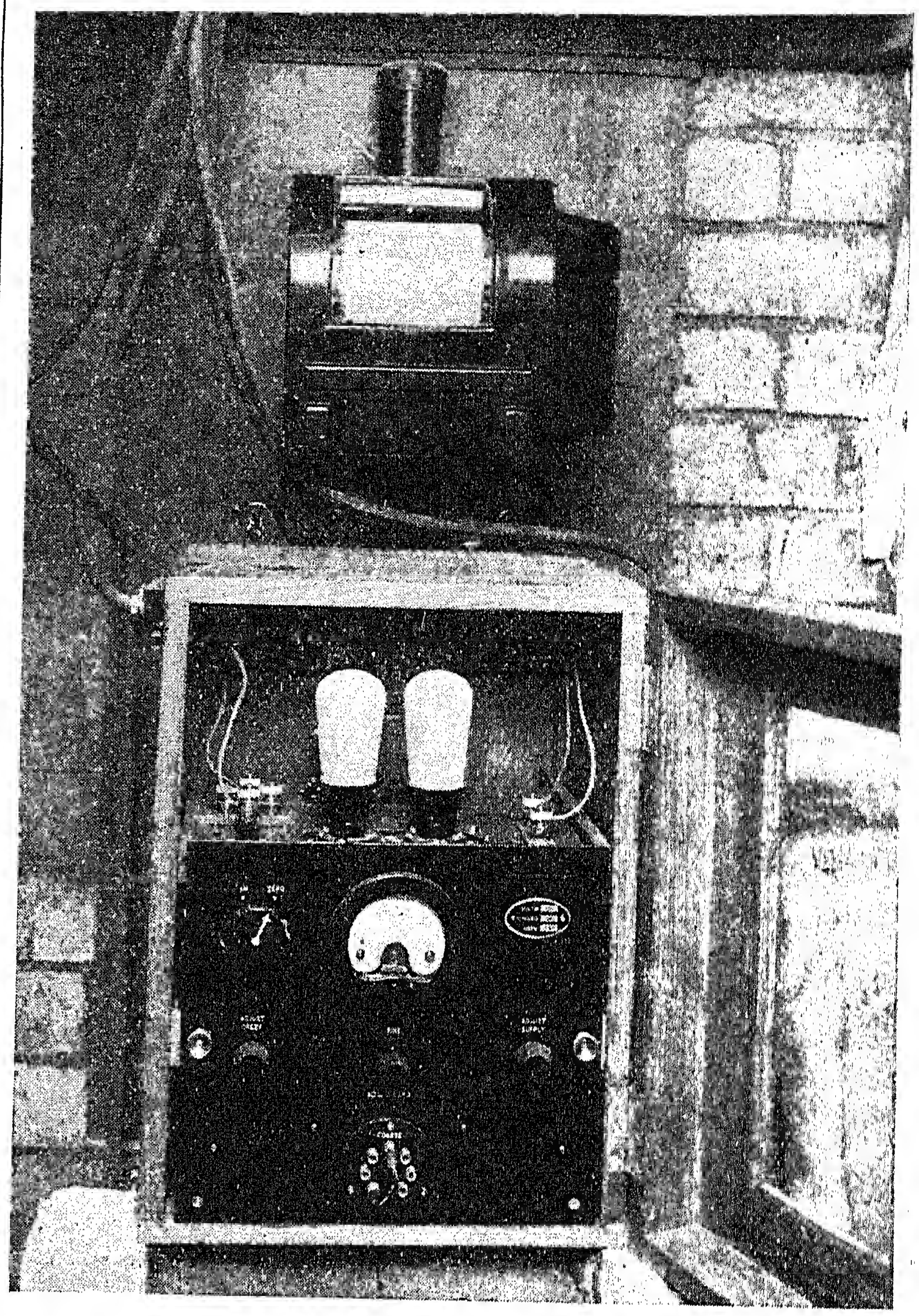


Fig. 6a.—First commercial "all-mains" thermionic potentiometer and recorder.

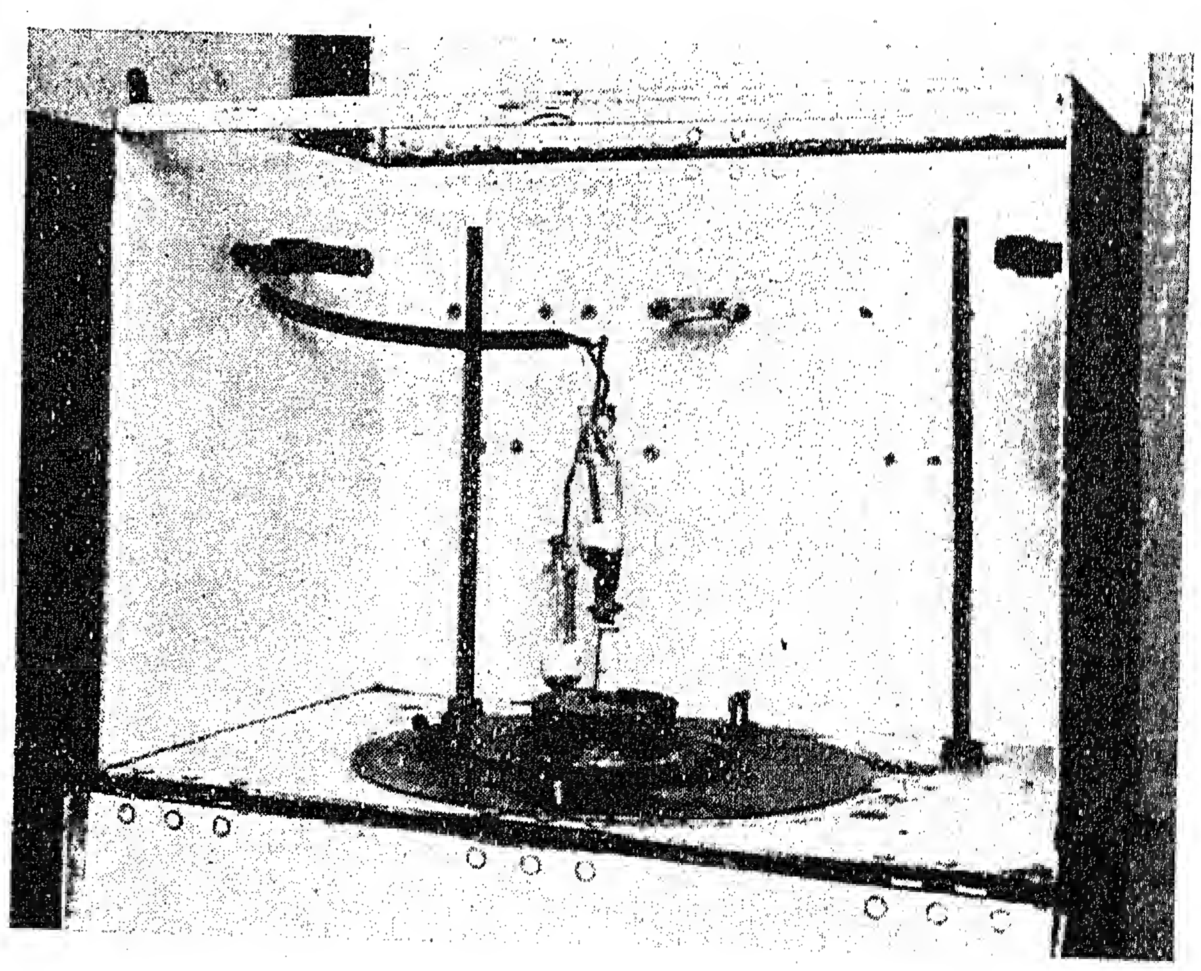


Fig. 6b.—Top of continuous liquor-sampling cell, showing electrodes.

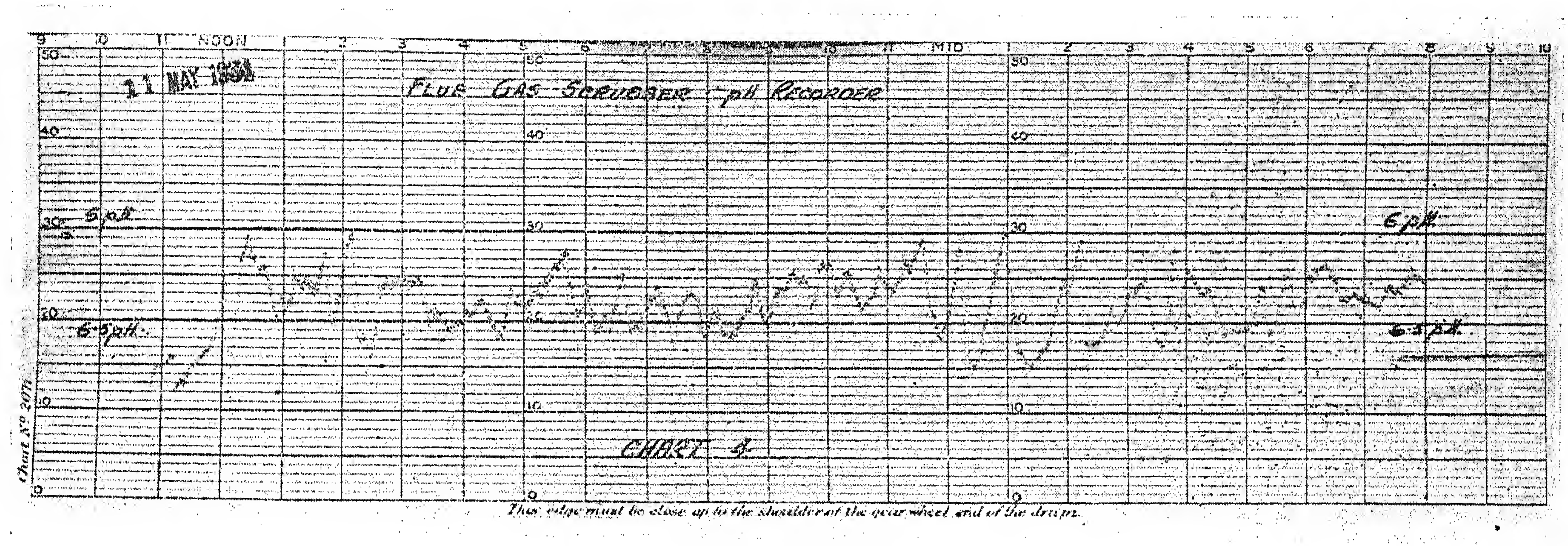


Fig. 6c.—Typical pH recorder chart, obtained by manual control of the lime addition on the pilot plant. The straight line on the extreme right is the potentiometer zero line.

to the liquor, at a rate equivalent to the "acid" constituents absorbed. Hence, by controlling the alkali addition from the readings of a pH recorder, the correct quantity of alkali can be added—without wastage on the one hand, and on the other without risk of producing acid and corrosive liquor and without diminishing the efficiency of extraction.

The pH of a liquor containing suspended solids and dissolved sulphites cannot be determined by the ordinary hydrogen or quinhydrone electrodes. A battery-operated pH recorder, using a glass electrode, had actually been

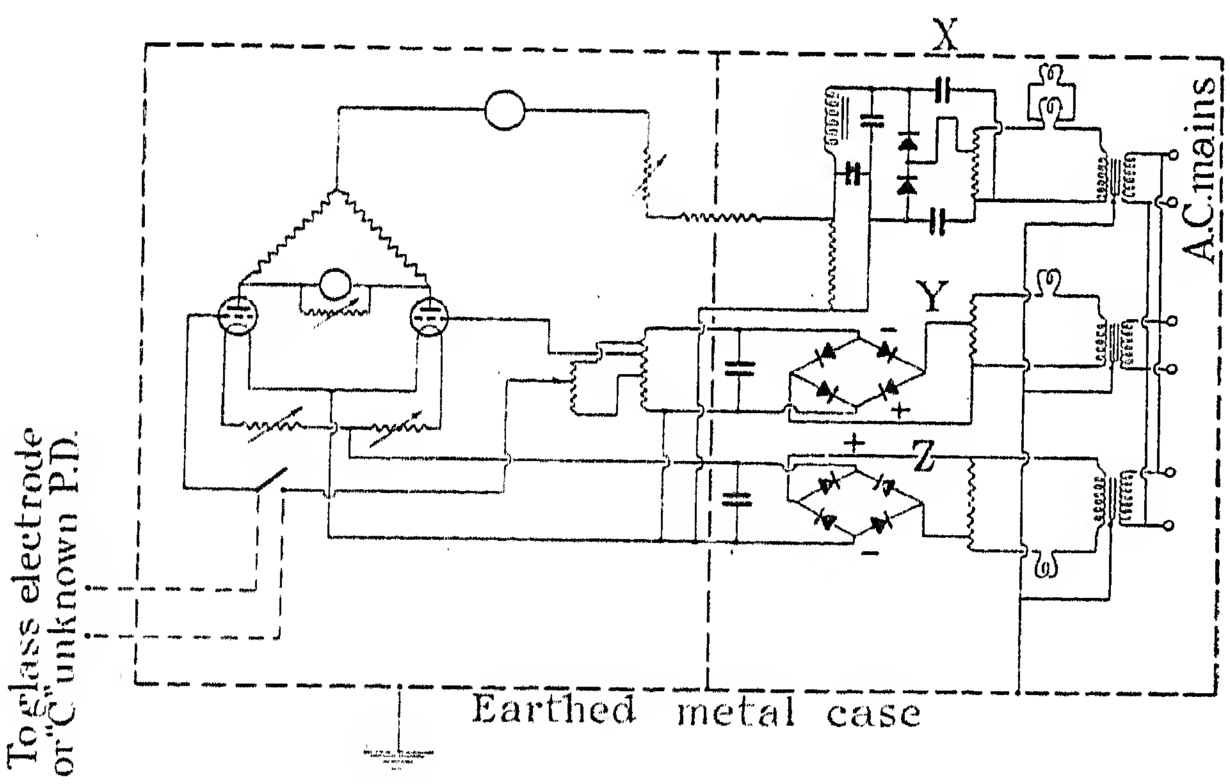


Fig. 7.—Circuit diagram of first experimental "all mains" thermionic potentiometer. The smoothing and rectifying side of this set has now been considerably simplified.

developed some three years earlier; several sets had been tried out and were in use under practical conditions. So far as the authors know, the fundamental circuit of this battery-operated pH recorder, which has been fully described in the literature, was the first, and remains the only, example of this important class of instrument to be developed successfully for normal commercial application. In applying it to the flue-gas scrubber, however, the authors decided that it should be applied as an "all-mains" instrument. The necessary modifications were found to be extremely difficult to achieve satisfactorily. Complete success was achieved in this direction, however, after about 8 months' effort.

The successful development of a robust all-mains instrument meant that continuous, accurate, and ready control could be applied to the pilot-plant scrubber, and it contributed very largely to the rapidity with which the

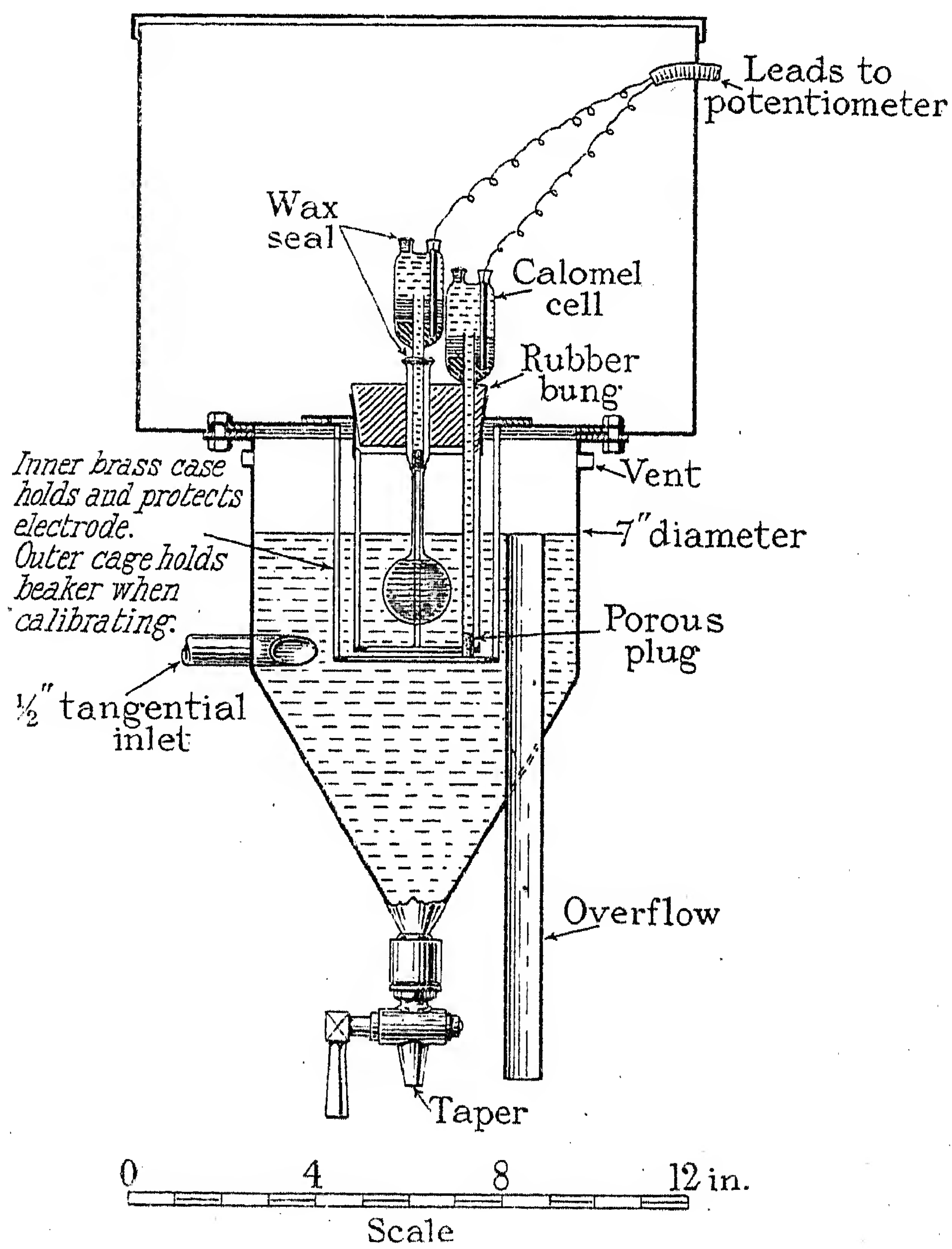


Fig. 8.—Section through continuous liquor-sampling cell for pH recorder.

further work proceeded, and to the complete success eventually obtained with a non-scaling, non-effluent system. A full description of the latest form of this pH recorder will shortly be available to all through the Cambridge Instrument Co., with whom arrangements

have been made to manufacture and market the instrument. The first of the commercial instruments is shown in Fig. 6, while the potentiometer and all-mains circuits employed with the instruments on the pilot plant are illustrated in Fig. 7. The arrangement of the liquor-sampling cell with glass and calomel electrodes is shown in Fig. 8.

Apart from the pH recorder, the only other control necessary for the plant is that governing the amount of liquor purged to the settlers from the main circulating system, in order to enable the solids accumulating in the system to be removed. This is readily done on the readings of a slurry density recorder such as the Andrews-Riley continuous density recorder.

Plant control has thus been thoroughly simplified and made independent of complex liquor and gas analyses, and of the long delays and "lag" periods which otherwise would have been inevitable.

Having thus dealt with the major principles underlying our process, we can now pass on to a description of the complete process and of the principles of design.

Section III.—DESCRIPTION AND DESIGN PRINCIPLES OF THE COMPLETE PROCESS.

A. Chief Items of Design.

The final details of design and operation of a plant working on the lines generally indicated in Section II have been thoroughly delineated, explored, and confirmed by continuous tests, extending over a period of 20 months, on a full-scale experimental plant unit installed on a boiler plant. A full description of this pilot plant, together with typical records of the performance, is given in Section IV.

In the present Section attention will be mainly directed to the principles of design in plant incorporating the developed process and diagrammatically illustrated in Fig. 9. For this purpose the following items will be considered in the order mentioned:—

(i) Dimensions of scrubbing towers (with normal and high-sulphur coals);

(ii) Scale prevention and its incidence on—

- (*a*) size of delay tank,
- (*b*) liquor rate through scrubber;

(iii) Purge to solids-separation plant and return of clarified liquor;

(iv) Starting and stopping the plant;

(v) Choice of alkali;

(vi) Mal-operation of plant and ease of cleaning;

(vii) Modified system with purge to drain, as allowable in exceptional cases.

B. Dimensions of Scrubbing Tower.

The cross-sectional area required in the vertical counter-current scrubbing or absorption towers is determined by considerations of:—

(*a*) The gas quantity;

(*b*) The designed maximum degree of supersaturation to be permitted in the scrubber.

Up to about 1·75 per cent of sulphur in the coal, the first of these fixes the cross-sectional area; with higher-sulphur coals the second is the determining factor in this respect.

Beyond a critical gas rate, the pressure-drop through the packing begins to rise sharply and is followed by the stripping of the liquor film from the packing. This will result in the formation of a fine spray in the gas and may cause ash and scale adhesion to those parts of the packing which are not properly irrigated. There is thus a maximum gas rate which should not be exceeded. This rate is equivalent to a velocity of approximately 5·0 ft. per sec. through the "empty" tower. A "working" velocity 10 per cent below this is taken.

Every packing has a useful range of liquor rate per inch periphery, as fixed between a minimum below which some of the packing surface would not be irrigated, and a maximum above which cascading or liquor logging would intervene. With the higher-sulphur coals, the liquor rate to give the permissible degree of slight supersaturation would be above the useful range for the packing, if the cross-sectional area of the scrubber were fixed by the nominal gas rate given above. This area has, therefore, to be increased and is thus dependent on the mass rate of SO_2 fed to the scrubber, instead of the actual flue-gas quantity. For flue-gas scrubbing the useful liquor rate with the grid packing employed is between 16 and 28 galls. per min. per sq. ft. of cross-sectional tower area.

Although the volume of water re-circulated over the packing is large, the height through which it is pumped is low and consequently the power consumption by the pumps is only about 9 kWh per ton of coal fired on full load. The water rate may be reduced *pari passu* with the gas rate to 60 per cent full load, provided that the conditions for preventing scale are maintained as outlined above. It is to be noted that this flexibility is not given in other types of wet washing plant which require a constant water rate at all loads.

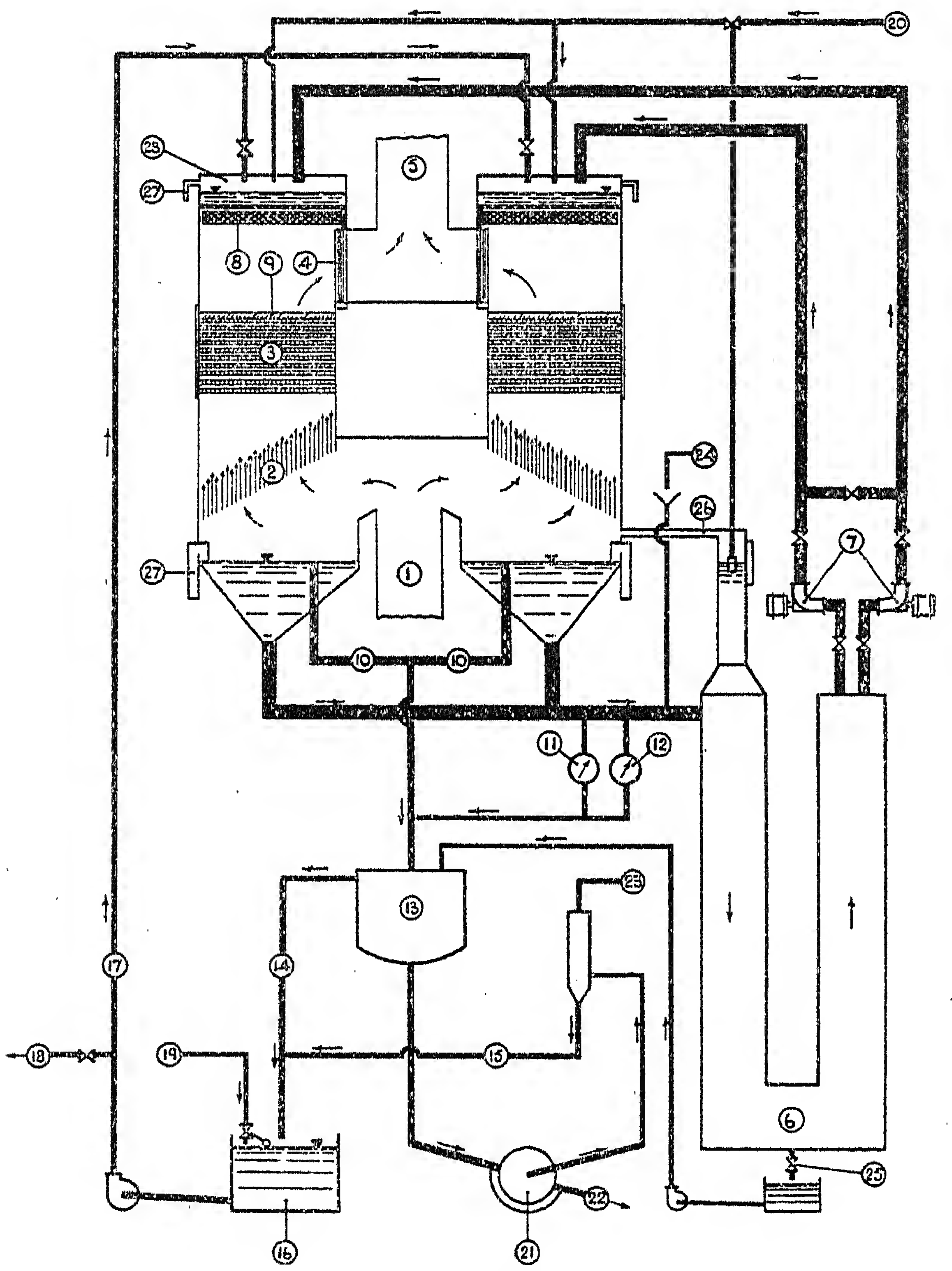
The depth of packing (i.e. of the main bulk of the packing, or of 3 in Fig. 9) depends upon the required end conditions of the flue gas, or, in terms of more general but less logical use, upon the extraction efficiencies required. In general a 3 ft. 6 in. depth of packing will take out all the dust above 10 microns, and a very large proportion (over 90 per cent) of that below 10 microns. It will give about 98 per cent sulphur removal from burning an average coal, with about the same efficiency of dust extraction for pulverized-fuel firing, and slightly less for stoker firing. It will, of course, take out all the grit. A depth of 3 ft. 6 in. thus tends to become a standard dimension, although a greater depth will give even higher extraction efficiencies.

Below the grid packing comes the special packing with a high "scaling resistance." This in practice constitutes about 15 per cent of the total "packing surface," and is in the form of suspended wood plates (2 ft. 6 in. to 3 ft. 6 in. deep), pitched at between 2 in. and 3 in. intervals, and carrying pear-sectioned liquor collectors on their top edges (see 2 in Fig. 9). These collectors, with the appropriate spacing and depth of the plates, ensure higher liquor rates and velocities than pertain to the grid packing, and confer a higher scaling resistance exactly where it is wanted.

The deep plates actually curtail the height of the

towers, since they also act as gas distributors and thereby eliminate a section of tower that would otherwise be required to give vertical direction and distribution to the gas after entry from the side. Tower height is made up almost entirely of:—

(*a*) Grid packing depth;
(*b*) Gas entry and exit ports;
(*c*) Liquor feed tank and primary distributors at top of scrubber;
(*d*) Liquor-collecting hopper at bottom of scrubber.



1. Gas inlet.
2. Primary elements.
3. Grid packing.
4. Spray eliminators.
5. Gas outlet.
6. Delay tank.
7. Re-circulation pumps.
8. Liquor distributors.
9. Film feeders.
10. Purge.
11. pH recorder.
12. Solids recorder.
13. Settler.
14. Clarified liquor from settler.
15. Clarified liquor from filter.
16. Mixed liquor tank.
17. Mixed liquor return.
18. To alkali preparation plant.
19. Make-up water supply.
20. Emergency make-up water supply.
21. Rotary vacuum filter.
22. De-watered solids (rejected from system).
23. To vacuum pump.
24. Alkali supply and control.
25. Delay tank sludge cock.
26. Pressure-equalizing pipe.
27. Emergency overflows.
28. Liquor head tank.

FIG. 9.—Diagrammatic arrangement of complete non-effluent flue-gas scrubbing plant (excluding lime slurry preparation section).

It is of importance to keep the vertical distance between the liquor levels in the bottom collecting hopper and the top feed tank as short as practicable, since this distance determines the head on the main circulating pumps (see 7, Fig. 9). The main item in tower height is that made up of gas entry and exit ports, on the basis of actual gas velocities of 12 ft. per sec. at entry and 6 ft. per sec. at exit, the latter being fixed for purposes of spray elimination (see 4, Fig. 9).

The great efficiency of the grid form of packing described above leads to practically complete saturation with water vapour of the flue gases leaving the scrubber. The exit gases and the circulating liquor therefore assume the "wet bulb" temperature of the inlet gas. This temperature can be obtained approximately from tables connecting the wet and dry bulb temperatures with the moisture content of air, and for modern boiler plants this temperature is around 120° F.

C. Scale Prevention in Design.

The principles underlying scale prevention have already been discussed in Section II C. In practice, immunity from scaling is provided by:—

(i) Holding the liquor, before re-circulation, in a delay tank for a time sufficient to ensure the removal of the necessary proportion of supersaturation produced by one liquor cycle through the scrubber. The delay time is partially dependent on the seeding surface afforded by the solids in suspension in the liquor, the seeding surface being provided by the crystals of calcium sulphite and sulphate present in the circulating liquor, and controlled by the amount of purge to the settlers;

(ii) Apportioning the liquor rate so that the degree of supersaturation at the scrubber exit (arising when a saturated solution enters at the top) is not sufficient to overcome the scaling resistance of the bottom packing;

(iii) Choosing a material, a form, and a liquor velocity, for the bottom packing to give the required scaling resistance.

The authors found that with wood grid packing the total delay time should be about 14 minutes per grain equivalent of sulphur per gallon, absorbed and oxidized within the scrubber to calcium sulphate in one liquor cycle, when the suspended seeding calcium sulphate is over 2·5 per cent by weight.

Similar considerations apply also to the prevention of scaling by calcium sulphite, except for the added differences that: (*a*) Supersaturation with calcium sulphite solution appears to be more easily destroyed by seeding; and (*b*) the solubility of calcium sulphite varies widely with pH variation.

With correct lime addition the pH changes to 6·8 from 6·3 at the scrubber exit. If the lime is added before the delay tank, there is then an appreciable reduction in the concentration of dissolved calcium sulphite, owing to the reduced solubility at the higher pH. The pH of the liquor changes back to 6·3 at the scrubber exit on the next cycle.

By virtue of this cyclic change in pH and of the accompanying change in solubility of calcium sulphite, it is possible to run under certain circumstances so that calcium sulphite not only does not attain any measurable degree of supersaturation, but does not even attain saturation in solution within the scrubber. The imposition of such a pH cycle on the main liquor circulating system, for preventing scale formation, should be compared with the imposition of thermal and time cycles discussed under Section II C.

Typical experimental figures for the change in solu-

bility of calcium sulphite with change in pH are given in Table 2.

The authors found, in general, that with the grid packing described and with lime neutralization, the total delay time should be about 9 minutes per grain equivalent per gallon of sulphur absorbed and leaving the scrubber as $CaSO_3$ for each liquor cycle, when the suspended calcium sulphite is over 2·5 per cent.

The two delay times given in terms of sulphite and sulphate make, fix, according to which is the greater, the size of delay vessel (6 in Fig. 9) when the permitted rate of make, or supersaturation, is known. In general,

TABLE 2.

Change of Solubility of $CaSO_3$ with pH at 122° F. (50° C.).

Ion	Composition of solution—concentration of ions in grain equivalents per gallon			
	Synthetic liquor		Liquor taken from a boiler flue-gas scrubber	
Ca	2·15	3·78	3·36	2·91
Mg	—	17·50	19·05	22·70
Na	—	31·50	32·80	37·10
SO_4	1·75	12·95	15·70	20·60
Cl	—	38·50	39·20	41·20
	Solubility of $CaSO_3$ in above solutions, expressed in grain equivalents per gallon at pH shown on left			
pH				
7·0	0·161	0·217	0·392	—
6·8	0·217	0·252	0·434	0·518
6·6	0·231	0·293	0·469	0·588
6·4	0·245	0·315	0·484	0·615
6·2	0·252	0·392	0·540	0·637
6·0	0·259	—	—	—
Increase in solubility over pH range 6·8–6·2	0·035	0·140	0·106	0·119

for the usual wood "grid and plate" packing already described, this is approximately just under 0·2 grain equivalent per gallon of liquor for sulphur absorbed and oxidized in the scrubber. The corresponding figure for sulphite sulphur is higher than this owing to the change in solubility with increasing pH, a consideration of some importance with high-sulphur coals and relatively low oxidation in the scrubber. Thus the permitted rate of make of sulphur per cycle is as high as 0·33 grain equivalent per gallon. These permitted rates of make are the maxima for complete immunity from scaling and, in conjunction with the flue-gas quantities, determine the circulating liquor rate.

D. Separation and Discard of Solids, and Return of Clarified Liquor.

The solids in suspension in the circulating liquor are maintained at a concentration of approximately 10 to 15 per cent by weight in order to: (*a*) Keep down to reasonably small quantities the amount of liquor fed to the solids separation section; and (*b*) provide substantial seeding surface, or crystallization nuclei, thereby reducing the size of the delay tank.

The solids in suspension are maintained at the required concentration by controlling the rate of purge to the settlers in accordance with the readings of a density indicator.

It has already been remarked that lime addition should take place between the scrubber and the delay tank with a view to utilizing to the full the advantage of reduced sulphite solubility (24, Fig. 9). Clearly the purge (10, Fig. 9) to the settlers should be taken from between the scrubber and the point of lime addition in order to: (*a*) Reduce the loss of alkali in the solids discarded; and (*b*) reduce slightly the size of the delay tank.

The thickened mud from the settler contains 30 to 40 per cent solids and may be further de-watered on rotary vacuum filters, of the disc or drum type, down to about 30 to 45 per cent of water, dependent on the fineness of the ash collected from the flue gas.

It is possible to dispense with settlers and filters and to use continuous, automatically discharging centrifuges. The authors found that it is thus possible to get down, in one operation, to a mud containing about 45 per cent of water; but their experience in this connection is not yet sufficiently extensive to warrant a definitely favourable recommendation. Although the power consumption with centrifuges may be a little greater than with settlers and filters, their low capital costs and small space requirements are very attractive and may render their use economical in many situations.

The clarified liquor from the settlers and filters, or from the centrifuges, is returned to the main circulating liquor system either directly or indirectly (16, 17, and 18, Fig. 9). In the former case it should be returned after the delay tank and before the scrubber, for obvious reasons—preferably to the liquor head tank. In the latter case it is used for the preparation of the lime or chalk slurry, containing 7 to 12 per cent suspended lime or chalk and returned, as previously indicated, immediately before the delay tank.

When using settlers it is not necessary to design them for complete clarification of the "return liquor." The size of the settlers can be cut down by increasing the liquor feed and budgeting for, say, 70 per cent clarification.

The methods of disposing of the solids will obviously vary with the locality. The solids make good "fill," and would be valuable for land-reclamation purposes owing to their consolidating properties; but in many cases they will be dumped out at sea.

E. Starting and Stopping the Scrubbing Plant.

Although it is necessary to run the plant with a high concentration of suspended solids, scaling does not occur if the plant is started up on pure water if the solids are allowed to accumulate rapidly in the system. On the other hand, it is inadvisable to do this frequently. Consequently, small cross-connections are arranged between the scrubber circulating pumps through which the delay tanks of standing scrubbers may be filled from running plants.

On shutting down, it is essential to wash out the packing with clean water in order to prevent crystallization of the liquor on the surfaces as they become dry (such crystals would form seeds on which scale would deposit). Furthermore, it is necessary to keep the wood packing moist by occasional flushes of water during idle periods. This is particularly necessary in plants where the scrubbers are situated above the boilers.

F. Choice of Alkali (Lime versus Chalk).

On technical grounds, it is preferable to add the alkali as lime rather than chalk because:—

(*a*) Lime is the more reactive and uniform;

(*b*) The change in pH in the cycle is greater with lime, with some consequent beneficial effect on closeness and ease of plant control; and

(*c*) The greater change in pH enables a smaller scrubber to be used for flue gases resulting from burning the higher-sulphur coals.

In order to avoid corrosion of the scrubber hopper, it is necessary to keep the minimum pH of the liquor above 6·0. Hence the chalk used must be finely ground and fairly reactive if it is to be rapidly dissolved by the CO_2 in solution, and if no great excess is to be used. The authors have found that by-product (precipitated) chalk is perfectly satisfactory to use, but that some natural chalks, even when ground to pass 200 I.M.M. (240 B.S.I.) sieve, are not quite sufficiently reactive unless used in considerable excess.

During long-period tests, analyses for $CaCO_3$ in the discarded mud indicate that the consumption of a finely ground Kent whiting was about 35 per cent above the consumption of Buxton lime on an equivalent CaO basis, and that the consumption of lime is practically theoretical, in fact from 5 to 10 per cent less than theoretical with pulverized-fuel firing.

The reactivity of chalks may readily be compared in the laboratory by suspending samples in water, passing in CO_2 for a short specified time, and determining the amounts of chalk dissolved.

In many cases the deciding factor as to whether to use chalk or lime will be the comparative cost basis of equivalent CaO in the slurry stock tanks as corrected by a factor representing the actual consumption as a percentage of the theoretical. Freights and transport methods available will enter into this very largely, and each station will almost invariably require individual consideration. As a rough guide, however, it may be taken that chalk (with 43 per cent CaO and, say, 20 per cent moisture) at 8s. per ton delivered to site is equivalent to lime (with 96 per cent CaO) at about 25s. per ton delivered to site. These figures are but generically suggestive, and must be worked out in detail for individual application.

G. Mal-operation of Plant and Ease of Cleaning

If the plant is designed and worked on the lines indicated, the whole plant keeps clean and free from deposit. All kinds of plants, however, can be mal-operated, either deliberately or accidentally, and the scrubber is no exception to the rule. Thus, while the packing will remain clean if the plant is operated in accordance with the running instructions supplied, mal-operation may result in the packing becoming slightly dirty or covered with a light deposit.

It is inconceivable that the packing would become heavily scaled, since the indication of scale deposition would be soon reflected in the pressure-drop across the scrubber. This pressure-drop, normally, is utilized as the reading for a gas flowmeter, the scrubber packing corresponding to the more usual form of orifice plate.

In the unlikely event of the scrubber packing becoming slightly scaled, chemical cleaning of the packing is easier and cheaper than mechanical cleaning. The applied design of commercial installations allows immediate and full access to the packing *after* the scrubber has been taken off the line; this, in "unit" as opposed to "central" installations, would be *after* the boiler has been taken off the line, or perhaps after it has been put to "stand by" where regulations are lax, and a small flue-gas by-pass is permitted for emergencies. All the packing in a scrubber for a large boiler could be taken out and replaced as a rush job within two hours.

On the other hand, chemical cleaning can be applied while the scrubber is in operation, preferably on one-quarter to one-half gas load, with a view to keeping down the cost. Such cleaning means a change-over in the alkali used, from lime or chalk to soda ash, which is a more expensive form of alkali.

The liquor system of the scrubber concerned is drained and filled with water and then run with soda as alkali for 12 to 24 hours. As a spare alkali line is always provided with commercial plants it is not necessary to change all the scrubbers over to soda.

When cleaning in this way, the pH is held at 7·0 to 7·5 and water is added at a rate sufficient to necessitate a purge, from the circulating system, of about 6 tons of water per ton of coal fired. This purge need not be put to drain, but may be used as make-up on the other scrubbers still running, with the usual lime or chalk treatment.

Under the conditions just described for the scrubber being cleaned, the soda reacts with the calcium sulphate and sulphite scale to form calcium carbonate, which is itself dissolved by the CO_2 in the washing liquor. Sulphite scale is less readily removed than sulphate scale, owing to the lower solubility of the former, but in practice, owing to the designed conditions, the latter would normally preponderate in scale formed from mal-operation, such as from running with lower solids in suspension than allowed by the official minimum figures.

It may not always be possible to utilize completely, as make-up for the other scrubbers, the relatively large volume of purge obtained during soda cleaning of the one scrubber. Any excess which cannot be so used, or in fact all the purge from soda cleaning, can be put direct to drain (or river) without harm, provided that before doing so the sodium sulphite in solution is converted to sulphate by oxidation. This can readily be done in a small oxidizing tower, through which air is blown. A tower 2 ft. 6 in. square with a 6 ft. depth of 1 in. deep $\frac{1}{2}$ in. pitch wood grid packing will deal with the whole purge of 400 gallons per min. from a large boiler, and will require an air rate of 200 cub. ft. per min.

Such an oxidizer tower is generally provided for plants

where the restrictions on the purity of effluents to stream or river are rigid, for it may also be of service in oxidizing any excess liquor accumulating in the whole scrubber plant, e.g. on taking boilers off load. The amount of such effluent will be negligible in practice.

There is, of course, no difficulty in arranging that there shall not be even these small occasional effluents to drain. The oxidizer is then dispensed with, and the liquor capacities in the system are arranged to suit the specified conditions.

H. Re-circulating System with Continuous Purge to Drain, as Applicable under Exceptional Conditions.

Some few power stations may be very favourably situated as regards water supplies and absence of rigid effluent restrictions. For such cases the standard non-effluent system may be easily modified, in order to take advantage of the circumstances prevailing.

The delay tank becomes smaller, its size being determined by the delay period required to destroy only the calcium sulphite supersaturation arising when the lime is added. The purge to drain (i.e. discarded clarified liquor from the settlers) is adjusted so that the amount of water make-up in the system is just sufficient to prevent the circulating liquor from becoming saturated with respect to calcium sulphate. Before going to drain, the clarified liquor to be discarded may be oxidized in the manner mentioned above. With a make-up water of average SO_3 content (say, 2 grains per gallon), the purge required with 1 per cent sulphur coal roughly corresponds to 6 tons of water per ton of coal fired.

Under more exceptional and favourable circumstances still, the liquor to drain need not even be clarified, the raw purge being put to drain, e.g. to a marsh or bog. In these very few cases, the fortunate power station will not require any " solids " separation section at all.

Section IV.—DESCRIPTION AND PERFORMANCE OF THE PILOT PLANT AT BILLINGHAM.

A. Description of Pilot Plant.

The pilot plant has been in continuous operation from April, 1933, until December, 1934 (apart from a small fraction of this time, required for plant modifications). The general arrangement of the pilot plant, in its final stages of development, is shown in Fig. 10.

In order that the results obtained during the investigation should be directly applicable to the design of commercial installations of the largest type, the experimental scrubber was made to the dimensions and as a prototype of the full-scale cell or unit, of which a number (12 to 22), within two or four nests or shells, would constitute a scrubbing apparatus equal to the requirements of one large boiler. The experimental scrubbing tower was thus made 4 ft. square.

Fig. 10 shows clearly the lay-out of scrubbing tower

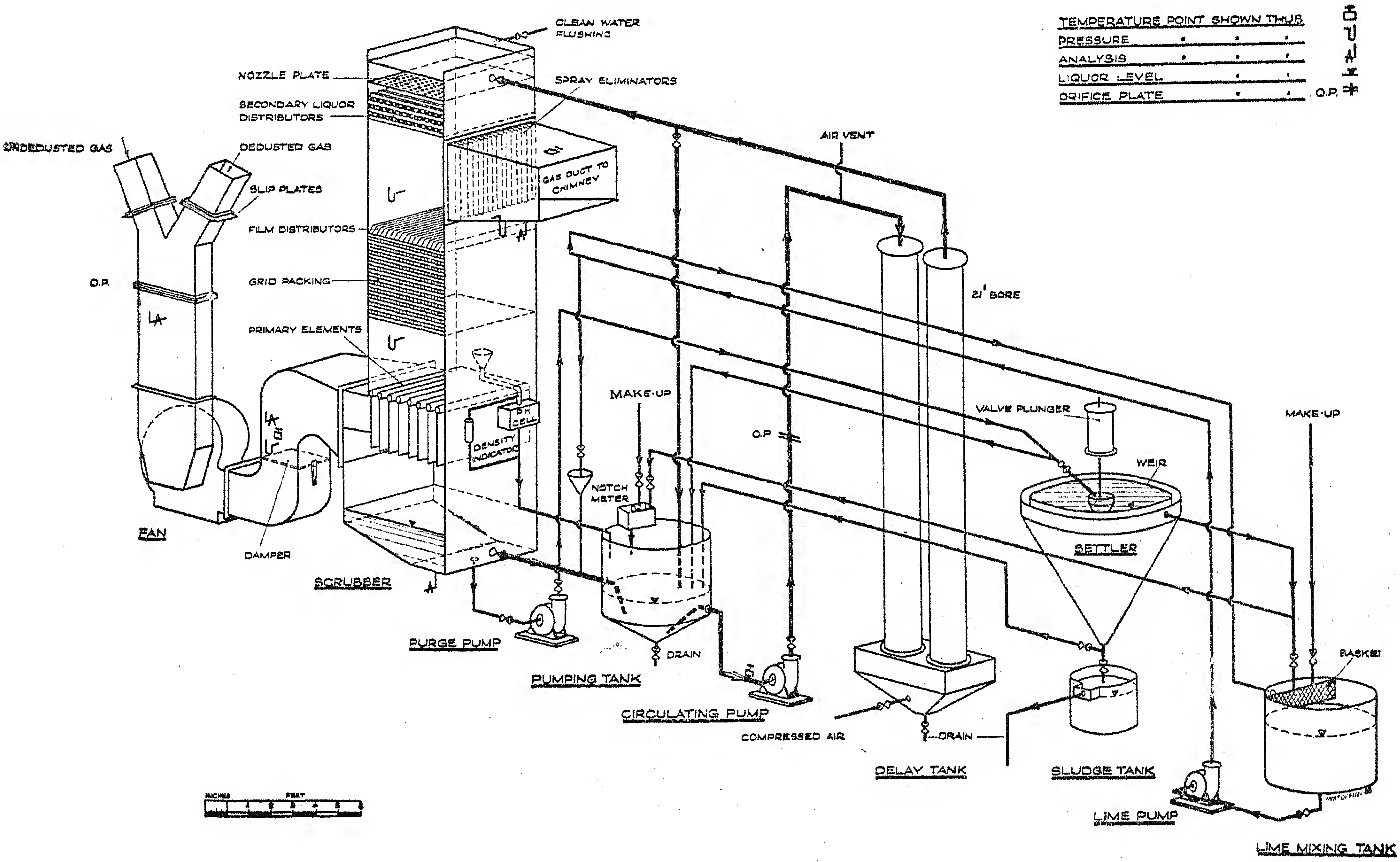


Fig. 10.—Isometric view of complete pilot plant.

delay tank, settler, and lime-preparation plant. Filtration of the sludge from the settler has been investigated on a 3 sq. ft. Rovac rotary vacuum filter and also by two well-known filter manufacturers.

Flue gas is drawn from a large powdered-fuel boiler. Connections to the flue of this boiler are so arranged that flue gas can be taken to the pilot scrubber from either immediately before or after one of the wetted vertical element type of dedusters, fitted some four or five years ago to the boiler.

When gas is taken from the latter of these two places, the conditions approximate roughly to testing with flue gas from a stoker-fired boiler. The gas, however, in this case is only at 180° F., and so the circulating liquor is steam-heated to the temperature which would be obtained when feeding gas at the normal temperature of 230° F.

Lime slurry addition is controlled manually from the readings of the pH recorder described in Section II E. The importance of this instrument, as the major and almost complete control of the process, cannot be overemphasized. Actually, no real steady running of the plant was obtained until the pH recorder had been perfected for use under the severe conditions of the experimental plant, situated as it was out in the open.

Rapid progress with the whole investigation became possible as soon as reliability was attained in the pH recorder, and the major outlines of the correct form of the non-effluent process were being drawn up towards the end of the first third of the time period covering this work in connection with boiler flue gases. The modified process with a purge to drain, as described at the end of Section III H, had been evolved in its major features a little earlier.

The last two-thirds of the time period have been spent in filling in the details of the correct form of the process, from the results of continuous long-period runs. Experience gained during the early running of the plant, before a delay tank had been incorporated, had demonstrated that slow scaling might not become appreciable until after 300 hours' running. The authors therefore decided not to accept the results of any test run of less than 500 hours' duration at full load, as evidence of freedom from scaling or silting or bird's nesting. Further experience confirmed the wisdom of this decision, and indicated that the final confirmatory tests should not be less than of 1 000 hours' duration.

B. Typical Operating Figures of the Developed Process.

Below, in Table 3, are given typical operating figures as representative of the daily records obtained during long continuous runs, during which the packing has remained perfectly clean. Some of the runs have been witnessed, or inspected, by representatives of independent authorities. In Table 3 are included typical figures for runs with pulverized-fuel firing and with pseudo-stoker firing, the conditions appertaining to the latter having been explained above.

C. Performance of the Pilot Plant with Reference to Extraction Efficiencies.

Numerous tests have been made on the pilot plant to determine its performance in the extraction of dust,

Table 3.

Operating Figures for the Pilot Plant.

General Conditions.

Packing:	
Primary elements $3 \cdot 7 \times 2 \cdot 88$ ft.	13
1 in. deep, $\frac{3}{4}$ in. pitch wooden grids, 4 sq. ft.	41
Depth of grid packing, ft.	3·5
Total surface area of grid packing, sq. ft.	1 820
Total surface area of grid packing, plus primary elements, sq. ft.	2 098
Gas Velocities:	
At inlet into scrubber at 220° F., ft. per sec.	13·8
Immediately under packing at 220° F., ft. per sec.	4·5
At exit through spray eliminators at 120° F., ft. per sec.	5·9
Pressure drop over whole tower, in. water gauge	1·2
Pressure drop over packing only, in. water gauge	0·8

Analysis of Coal Fired:

Ash = 13 per cent; S = 1·7–2·0 per cent.

Conditions for Pulverized-Fuel and Pseudo-Stoker Firing.

	Pulverized fuel	Pseudo-stoker firing
Equivalent rate of coal fired at $12\frac{1}{2}$ per cent CO_2, lb./hr.	1 100	1 140
Effective sulphur in coal fired, per cent	1·7–2·0	1·3–1·5
Maximum gas rate, cub. ft. per min. at N.T.P.	3 150	3 270
Circulating water rate, galls. per min.	260–440	260–440
Delay time, mins.	2·5–3·5	2·5–3·5
CO_2 in flue gas, per cent	12–14	10–13
Inlet gas temperature, ° F.	220	167
Exit gas temperature and circulating liquor temperature, ° F.	118	118
Typical concentration of suspended solids—		
$CaSO_4 . 2H_2O$, per cent	3·2	3·5
$CaSO_3 . 2H_2O$, per cent	2·9	10·0
$CaCO_3$, per cent	0·4	0·5
Ash, per cent	7·5	5·0
Total, per cent	14·0	19·0
Alkalinity of liquor at scrubber exit to methyl orange (pH 4·5), grain equivs. per gall.	0·2	0·2
pH at scrubber exit hopper	6·1	6·1
pH at scrubber inlet (head tank):—		
lime doping	6·9	6·9
chalk doping	6·5	6·5
Gas Analysis:		
Inlet—Dust, grains per cub. ft. at N.T.P.	6–13	0·6–1·3
Total sulphur, grains per cub. ft. at N.T.P.	0·5–0·8	0·4–0·6
Outlet—Dust, grains per cub. ft. at N.T.P.	0·1–0·2	0·06–0·13
Total sulphur, grains per cub. ft. at N.T.P.	0·01–0·02	0·008–0·012
Alkali Consumption:		
Maximum of theoretical equivalent of SO_2 absorbed, per cent	90	110

sulphur oxides, nitrogen oxides, and hydrogen chloride. The average efficiencies of removal are:—

	Percentage removal
For sulphur oxides	97–99
For nitrogen oxides	60–70
For hydrochloric acid	90–93
For grit and dust from pulverized-fuel boiler	97–98
For dust from pulverized-fuel boiler left in flue gas after having passed through a well-known wetted tube deduster	90–93

Since the total gas quantity going to the pilot plant was measured, it was possible to calculate with accuracy the rate at which gas should be drawn through the sampling nozzle. The dust filter consisted of four layers of finely woven cotton cloth wound round a wire former contained in a jar. Gas passed from the inside of the jar, through the filter and out through a tube, within the wire former, to an orifice plate flowmeter. After use, the innermost layers of the filter cloth were found to be quite clean—an excellent testimony to the efficiency of the filter cloth.

TABLE 4.

Typical Efficiency Figures for the Pilot Plant.

Concentrations in grains per cub. ft. at 68° F. = 2·29 mg per litre at 20° C. = 1 720 parts SO_2 per 10^6 parts gas. Lime neutralization, except where otherwise stated.

Type of flue gas*	Date	Gas rate, cub. ft. per min. at N.T.P.	Inlet	Exit	Efficiency	Depth of grid packing, ft. No primary elements fitted	Remarks
			Sulphur oxides + HCl, recorded as grains S per cub. ft.				
D	6/10/33	4 680	0·62	0·012	98·0	5 ft. steel	Overload gas rate
D	10/10/33	4 680	0·48	0·022	95·5	5 ft. steel	Overload gas rate, using chalk
U	22/ 5/34	3 160	0·73	0·018	97·5	3·5 ft. wood + 0·5 ft. steel	Normal gas rate
			HCl alone, recorded as grains HCl per cub. ft.				
U	26/ 5/34	3 160	0·037	0·0032	91	3·5 ft. wood + 0·5 ft. steel	—
U	27/ 6/34	3 160	0·085	0·0030	96	3·5 ft. wood	—
			Oxides of Nitrogen, recorded as grains N per cub. ft.				
U	24/ 5/34	3 160	0·070	0·027	61	3·5 ft. wood + 0·5 ft. steel	Average figures for NO content of retort and chain-grate-fired boilers were 0·03–0·04 grain N per cub. ft.
U	31/ 5/34	3 160	0·074	0·030	60	3·5 ft. wood + 0·5 ft. steel	
			Dust.				
D	17/ 8/33	4 580	0·795	0·055	93	5 ft. steel	Overload gas rate. General soot-blowing during test
D	10/10/33	4 680	1·13	0·113	90	5 ft. steel	
U	15/ 8/33	4 440	4·10	0·065	98	5 ft. steel	Overload gas rate. Combustion chamber soot blown
U	18/ 4/34	3 620	5·38	0·057	99	5 ft. steel	No soot-blowing
U	1/ 6/34	3 160	6·10	0·131	98	3·5 ft. wood + 0·5 ft. steel	No soot-blowing
U	25/ 6/34	3 160	3·96	0·109	97	3·5 ft. wood	General soot-blowing
U	26/ 6/34	3 160	4·85	0·083	98	3·5 ft. wood	No soot-blowing

* U = Undedusted gas direct from pulverized-fuel boiler. D = Dedusted gas direct from pulverized-fuel boiler, pseudo-stoker-fired conditions.

The tests with regard to the sulphur oxides were made by drawing samples of the gas through absorption bubblers, fitted with sintered glass dispersion plates, and containing N/10 or N/100 NaOH plus N/5 H_2O_2. The volume of gas passing the bubbler was measured on a rotary gas meter, and the excess alkali was titrated against standard acid.

The tests for dust performance were made according to the recommendations given in the 1932 Report of the Committee appointed by the Electricity Commissioners.*

* See Reference (1).

Table 4 illustrates the high efficiencies of extraction obtained with normal running of the pilot plant, which is easily capable of reducing the SO_2 content in the exit gas to below 20 parts per million by volume (0·01 grain sulphur per cub. ft.).

Fig. 11 shows photomicrographs of typical samples of dust collected on filters from before and after the pilot-plant scrubber, when fed with gas direct from a powdered-fuel boiler. The small size of such particles of dust as remain in the gas after the scrubber is well illustrated by some of these photographs, which show

that it is mostly less than 5 microns—aggregates formed during collection on the dust filters being neglected in this respect.

The authors have, on several occasions, given to Official Authorities a special and ocular demonstration of the remarkable efficiency given by the plant in the removal of fine particles. This demonstration is obtained by producing deliberately, and for a short time (sufficient for the demonstration), black smoke, by reducing the air feed to the combustion chamber of the boiler from which some of the flue gas passes to the scrubber. The portion of the flue gas issuing from the stack following the scrubber preserved the normal white appearance associated with its moisture content, and the white cloud rapidly and completely dissipated as usual. The remainder of the flue gas passing through another stack was dense black even although the gas had passed through the wetted vertical element deduster attached to the boiler concerned.

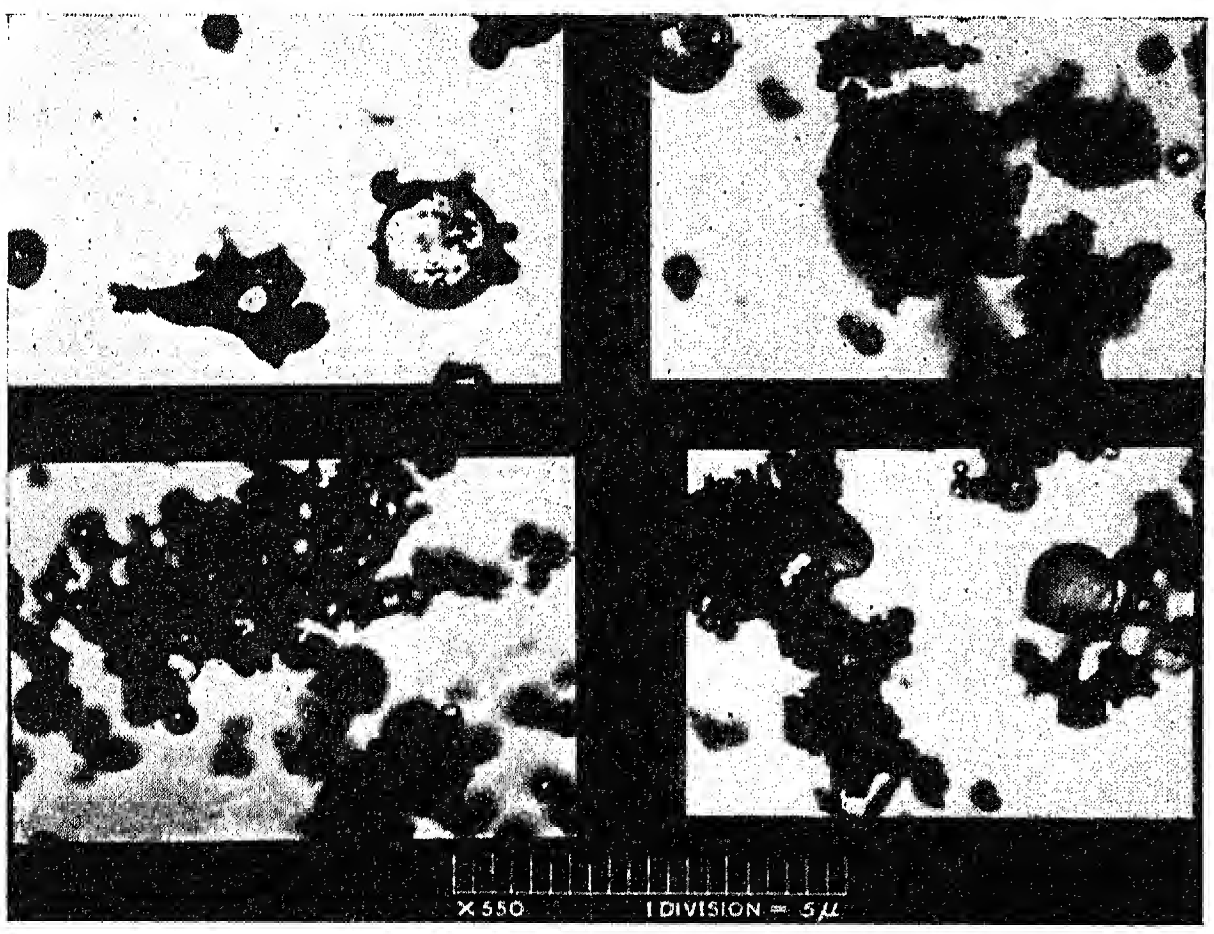
The exit gas from the plant is so free from SO_2 that it is practically odourless. So sensitive is the nose to minute concentrations of SO_2 that it is possible to tell at once when the concentration in the exit rises above 0·02 grain sulphur per cub. ft., as occurs when the pH of the liquor leaving the scrubber falls below about 5·8.

Provided the pH of the liquor at the scrubber exit is maintained above a general average of 6·2, corrosion of the scrubber hopper and shell is negligible. Although the pilot plant has been run under a variety of conditions and almost continuously for some 20 months, the $\frac{1}{4}$ in. mild steel plate forming the tower shell displays no appreciable or measurable thinning. The mild-steel duct-work for the gas exit is also in excellent condition.

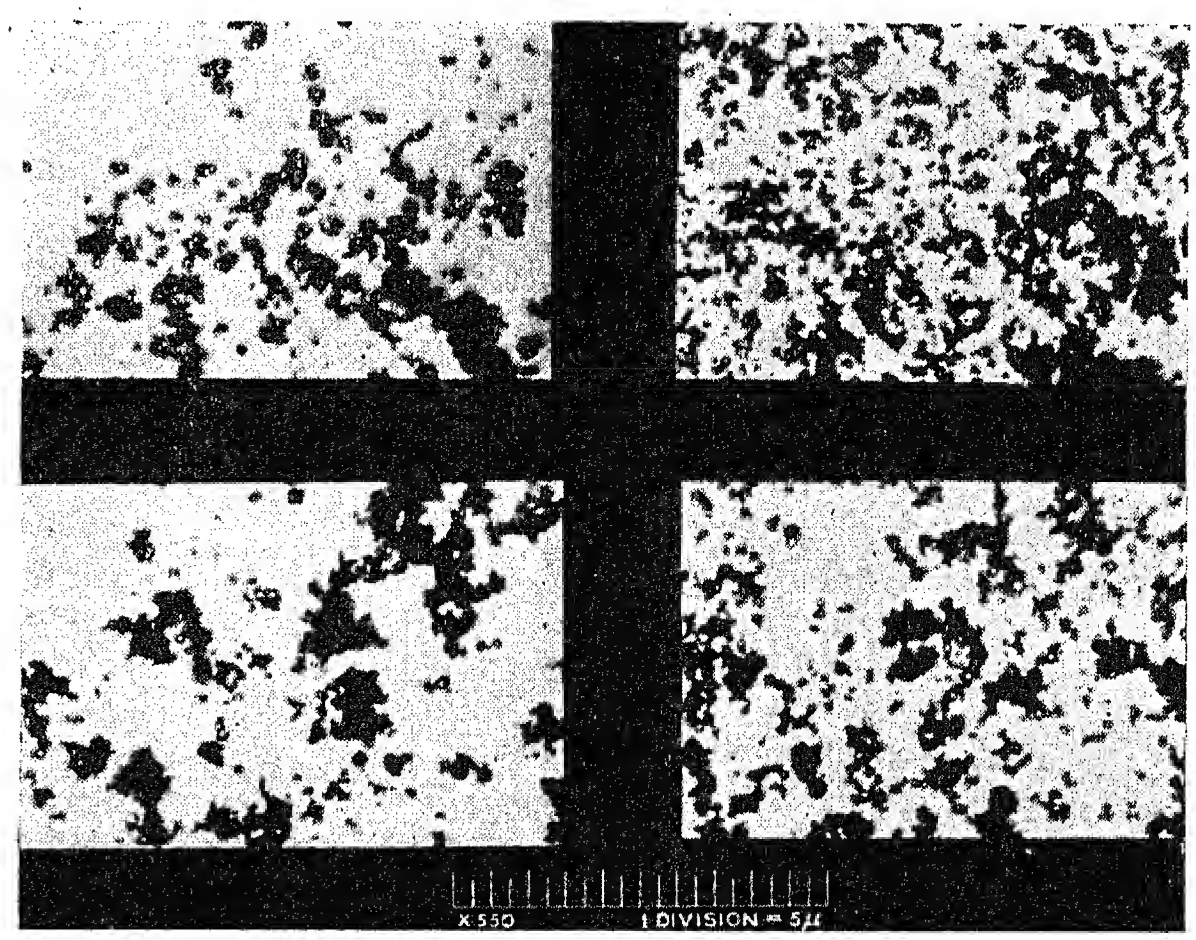
The lowest sections of the grid packing, and the suspended deep plates underneath, corrode at an appreciable rate if made of mild steel, owing to the local variations in pH arising there from the relatively rapid mass rate of SO_2 absorption. Grids and plates made of wood, corrosion-resisting steels, hard copper, and brass, are perfectly satisfactory.

Valves in the liquor pipe lines should not contain any dissimilar metals which can give rise to contact corrosion from a liquor containing dissolved CO_2. Mild-steel valves cannot be used for throttling the liquor, as the combined effect of erosion and corrosion then becomes serious. Rubber-lined valves of good design, however, can be used for this duty.

Since soluble sulphates attack ordinary Portland cement,* all tanks in concrete should be lined with a compact layer of aluminous cement.



Dust in gas before scrubber.



Dust in gas after scrubber.

Fig. 11.—Photomicrographs (× 550) of samples of dust collected on filters during operation of the pilot plant on flue gas from a powdered-fuel boiler. Note that these photographs have no bearing on dust concentration, but merely illustrate the size of the particles.

D. Mechanical Reliability of the Pilot Plant.

From the mechanical aspect, the plant is extremely simple since it consists only of tanks, slurry pumps, and pipes.

As the circulating liquor contains 10 to 20 per cent of abrasive solids in a liquor which is mildly corrosive owing to dissolved CO_2, it has been found advisable to: (i) Keep the velocities of liquor in mild steel or cast iron pipes below 7 ft. per second; (ii) line all "slurry" liquor bends with rubber; and (iii) use axial flow pumps in the main circulating system, the pumps having rubber-lined casings and rubber-lined or corrosion-resistant steel impellors.

E. Freedom from Scaling with the Pilot Plant.

With the correct methods of operation applying to the developed process, as described in Sections II and III, the immunity from scaling is best shown, perhaps, by the following details of the recent running of the plant over consecutive periods exceeding a total of 3 500 hours. During this time the test conditions were changed from time to time as indicated, but the essential operating methods were, of course, maintained throughout.

The test conditions referred to were as follows:—

(i) 900 hours on flue gas from a pulverized-fuel boiler, the gas being taken from before the wetted vertical

* See Reference (6).

element deduster fitted to the boiler. The plant was quite free from scale at the end of this run, but there was a bird's nest of a few inches diameter passing straight through the grid packing and registering with a corresponding choked patch in the primary liquor distributors under the scrubber head tank. It was found that these distributors had been incorrectly assembled.

(ii) 560 hours on gas from after the deduster just mentioned. First the liquor distributors were reassembled (a very simple operation) and the scrubber chemically cleaned with soda as described in Section III G.

(iii) 2 100 hours under a variety of testing conditions with gas from before and after the boiler deduster mentioned.

Except for the birds' nests that arose from inadvertence, the packing remained throughout as clean and free from scale as when it was new.

During the greater part of the above time the make-up water was a hard surface water drawn from a local stream. Tests of over 700 hours' duration are, however, included with make-up water from the estuary of a tidal river. This estuarial water is on the average over two-thirds sea-water.

Lime was used as alkali during the first two tests, but chalk was used for over 1 000 hours during the final tests.

Section V.—EXAMPLES OF THE PROCESS APPLIED TO LARGE BOILER PLANTS.

A. Typical Flow-sheet as applied to Powdered-Fuel Boiler Plant for a Power Station of 120 000 kW Installed Capacity.

The application of the process to large boiler plants may best be seen by considering a typical flow-sheet. For purposes of convenience a boiler installation with boilers of the capacity given on page 29 of the 1932 Report of the Committee appointed by the Electricity Commissioners* will be considered as an example:—

(a) *Station Capacity and Number of Boilers.*

Installed turbine capacity, kW	120 000
Number of boilers	8
Probable maximum number of boilers working on full load	6

(b) *Boiler Data.*

Maximum evaporation per boiler, lb. per hour	200 000
Maximum flue gas rate per boiler at 275° F. and 13 per cent CO_2, cub. ft. per min. ..	100 000
Peak gas rate at low CO_2 and maximum capacity of induced-draught fans, cub. ft. per min.	110 000
Peak coal consumption per boiler, lb. per hour	25 000
Analysis of coal:—	
Ash, per cent	13
Sulphur, per cent	1·5
Carbon in the ash, per cent	15

(c) *Lime Storage.*—The alkali storage necessary for a plant reasonably near to lime kilns or chalk supplies and a fairly low night load can be taken as:—

Lump lime in bunkers for 6 boilers on full load, days	3
Milk of lime slurry storage (7 per cent concentration), hours for 6 boilers	16

* See Reference (1).

(d) *Lime Consumption.*—The sulphur left in the ash is negligible. With powdered-fuel firing, experience has shown that the alkali consumption will not be greater than the theoretical equivalent of the sulphur in the coal, as a little alkali is also supplied by the ash.

Sulphur to scrubber per boiler, lb. per hour ..	375
Commercial lime requirement per boiler (95 per cent CaO), lb. per hour	691
7 per cent lime slurry flow per boiler (spec. grav. 1·05), galls. per min.	15·7
Total lime bunker requirement, tons	135
Volume of 7 per cent lime slurry storage tanks, galls.	90 000

The lime slurry is prepared in batch or rotary slakers of conventional design (usually as a 20 per cent slurry which is subsequently broken down). With lime slaking for 16 hours per day it is sufficient to install two pans (one spare) each of 4 tons per hour capacity. Rotary slakers require so little attention that usually they are run continuously.

Chalk slurry can be prepared in ordinary wash mills fitted with suitable screens or classifiers.

A small soda liquor storage tank is also required. The soda can readily be dissolved in the spare lime- or chalk-mixing pan.

The lime slurry is pumped in excess round one of two ring mains (one spare) feeding the scrubbers by one of two pumps in order to preserve continuity of supply. In order to avoid dead-ends, liable to chokage, the ring mains terminate in head tanks overflowing back to the storage tanks.

(e) *Scrubber Towers.*—Individual scrubber towers may be fitted above or alongside each boiler as in Fig. 12, or the flue gases may be led to one or two central scrubbing plants alongside the chimneys as in Fig. 15. In the latter case each plant would be subdivided by dampers into sections, each capable of taking the gas from one boiler. Since the gases are clean, induced-draught fans can be placed after the scrubbers:—

Minimum cross-sectional area of scrubbing tower per boiler required to avoid liquid carry-over at peak rate, sq. ft.	344

This area could be arranged, for example, in 16 cells, each 4 ft. 8 in. square, arranged in two nests. The total area of this arrangement would be 348 sq. ft.

Number of primary elements per boiler ..	256
Approximate size of each element, ft. ..	3·5×4·5
Total depth of grid packing ($\frac{3}{4}$ in. pitch, 1 in. deep), ft.	4
Free space in packing of $\frac{3}{32}$ in. strips, per cent	87
Surface area of grid packing, sq. ft.	45 200
Total washing surface per boiler, sq. ft. ..	53 250
Pressure-drop through scrubber and associated flues on full load, in. water gauge ..	1·6

(f) *Re-circulating Liquor System.*

Maximum liquor rate per scrubber, galls. per min.	9 500
Minimum liquor rate per scrubber, galls. per min.	6 300

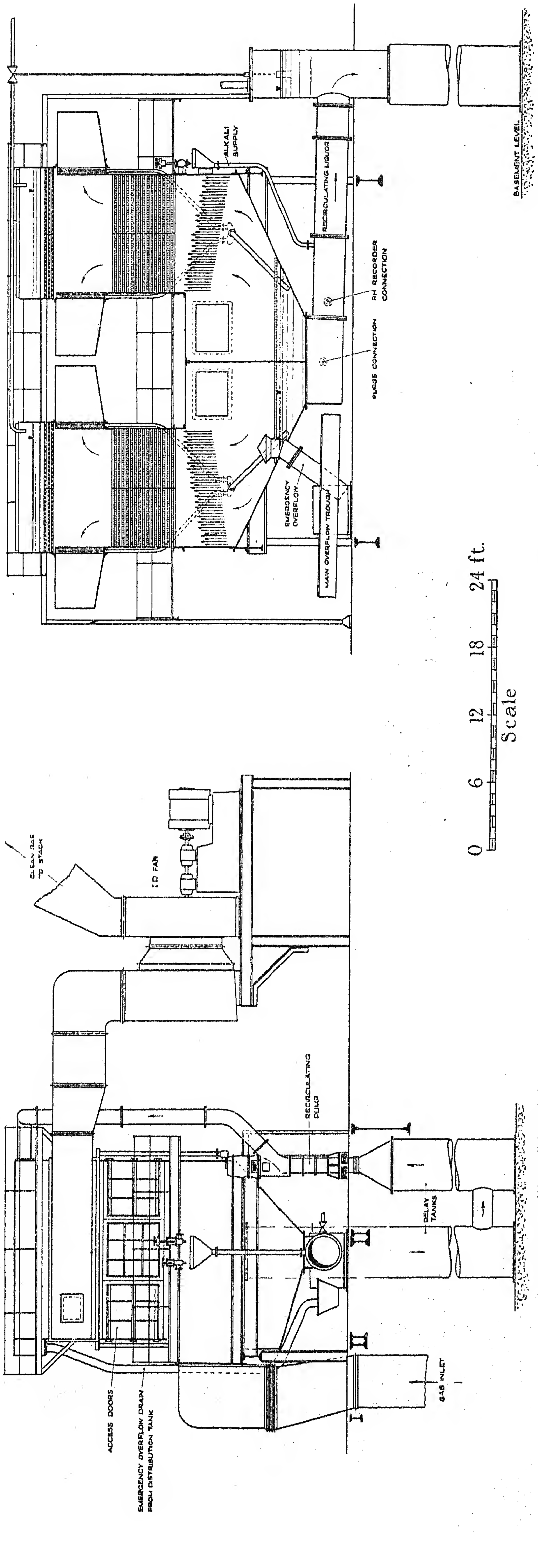


FIG. 12.—Flue-gas scrubber, with double outlet, for a boiler of 200 000 lb. per hour evaporation.

Liquor rate necessary to prevent dust adhesion and scaling with 1·5 per cent sulphur coal and full gas rate, galls. per min.	8 000
Minimum capacity of delay tank, pipes, scrubber head tank and hopper required for 2·7 minutes delay period, galls. ..	22 000
Total head above pumps, ft. water	30

It is advisable to install at least two working re-circulating liquor pumps on each scrubber, so that the water supply to the packing does not fail completely if one pump should trip out. The pumps should be fed from separate power distribution boards. If spare pump capacity is desired cheaply, three pumps can be installed for full output. Then, in the event of failure of one pump, it is possible to run the boiler up to two-thirds full load.

(*g*) *Composition of Flue Gas going to Atmosphere.*—Including soot-blowing periods, about 75 per cent of the total carbonaceous ash from the coal will pass to the scrubber. Of this 98 per cent will be absorbed.

Concentration of dust in inlet flue gas, grains dust per cub. ft. at N.T.P.	4·92
Concentration of dust in exit flue gas, grains dust per cub. ft. at N.T.P.	0·10
Total dust to atmosphere per boiler, lb. per hour	60
Concentration of sulphur oxides in inlet gas, grains S per cub. ft. at N.T.P.	0·64
Concentration of sulphur oxides in exit gas, grains S per cub. ft. at N.T.P.	0·013
Total sulphur oxides to atmosphere per boiler (as sulphur), lb. per hour	7·5

(*h*) *Solids formed in Scrubber Liquor.*—The extent of oxidation of the $CaSO_3$ to $CaSO_4$ within the system depends on the catalysts in the ash and lime, but 50 per cent oxidation is a fair assumption.

The solids formed per boiler are then:—

Ash and inerts from lime and excess

	lb./hr.	Percentage
$CaCO_3$	2 868	60·3
$CaSO_3 . 2H_2O$	897	18·9
$CaSO_4 . 2H_2O$	988	20·8
Total	4 753	100·0

The apparent $CaCO_3$ content of this mixture, after oxidation by H_2O_2, will be 3 to 5 per cent, depending on the alkalinity of the ash and the accuracy of the lime addition.

Maximum output of solids with 6 boilers on full load, tons per hour	13

(*j*) *Purge to Settling System.*—For scale prevention it is desirable to carry 3 per cent each of suspended calcium sulphite and sulphate in the circulating liquor. This is achieved by maintaining the concentration of total suspended solids above 14 per cent.

Hence, purge from one boiler with 100 per cent clarification (density 1·1), galls. per min.	51·5

(*k*) *Delay Time.*—The absorption of sulphur during each passage of the liquor (8 000 galls. per min.) through

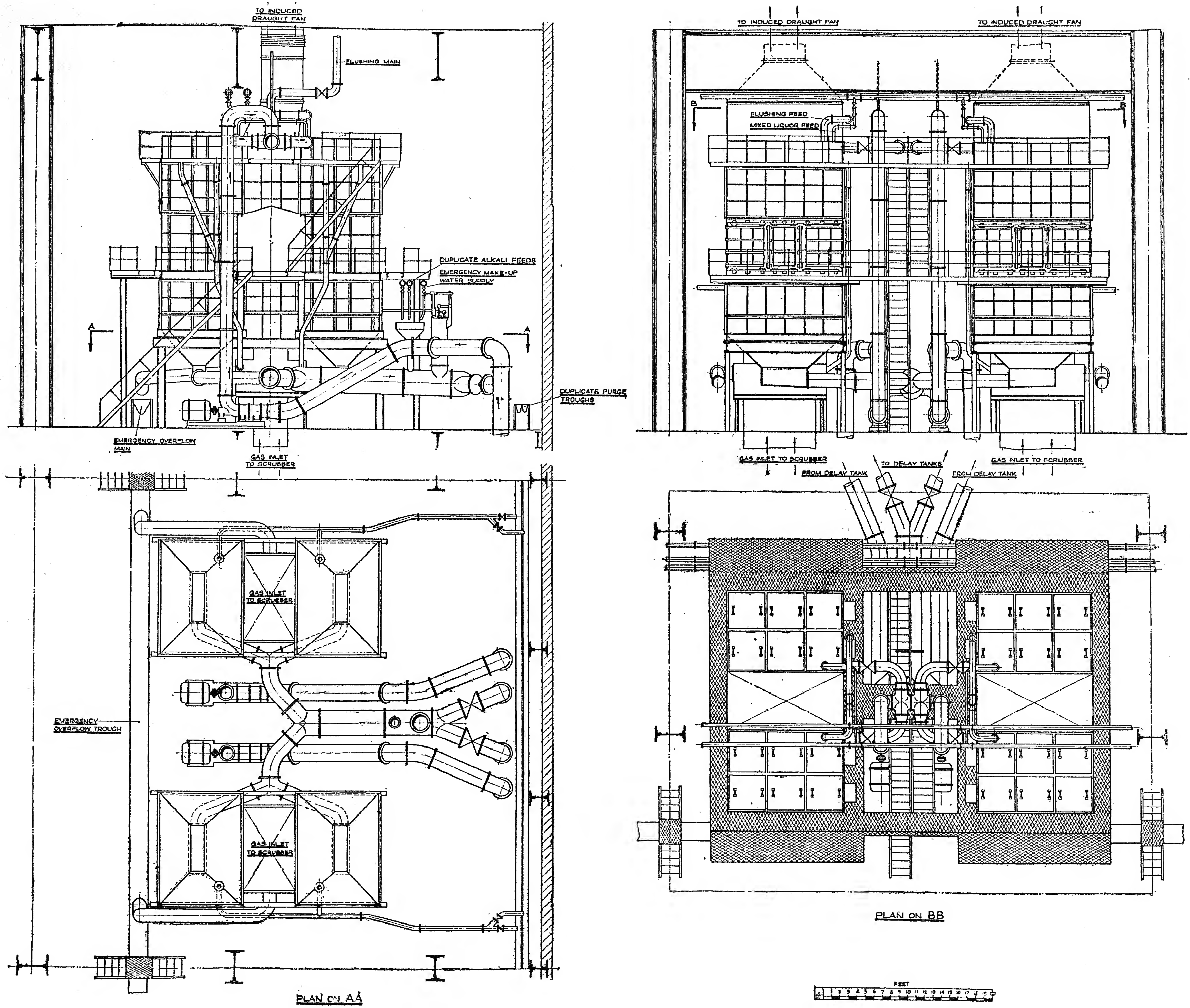


FIG. 13.—Flue-gas scrubber, with single inlet and outlet, for a boiler of 250 000 lb. per hour evaporation.

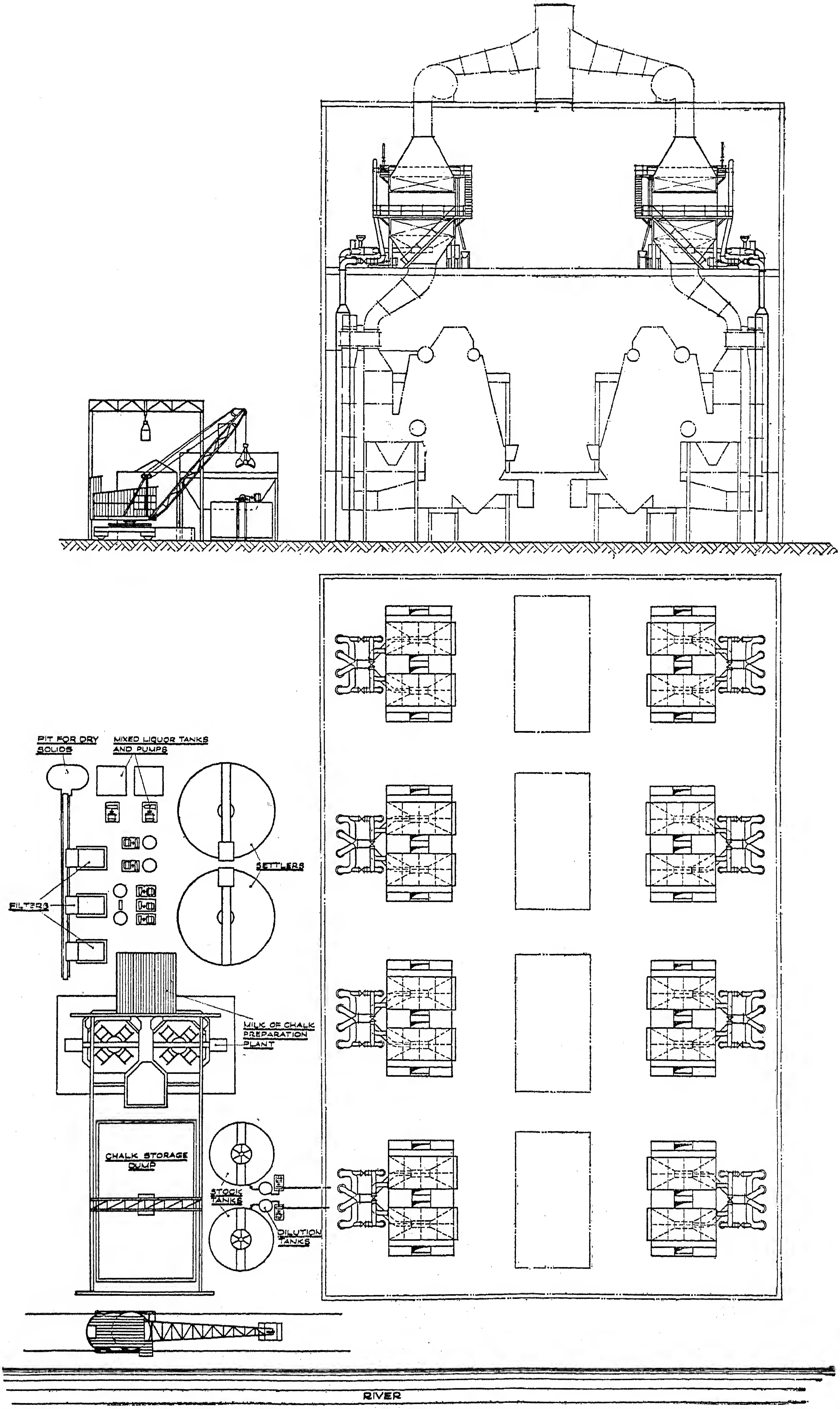


FIG. 14.—Plan of a " unit " flue-gas scrubber system for 8 boilers, each of 250 000 lb. per hour evaporation, showing settlers, filters, and lime plant.

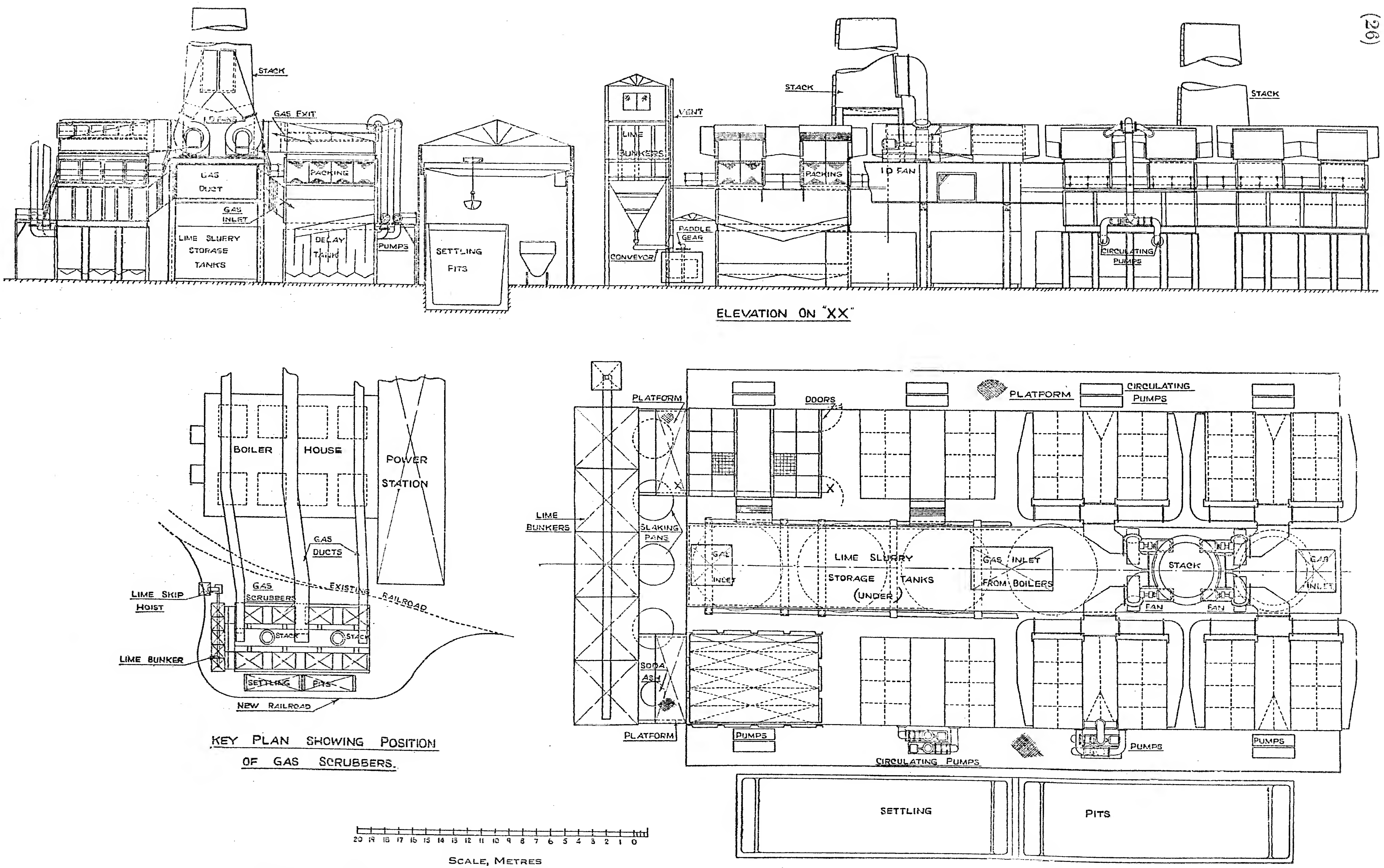


FIG. 15.—Plan of a complete central flue-gas scrubber system, with all auxiliaries, situated outside a boiler plant.

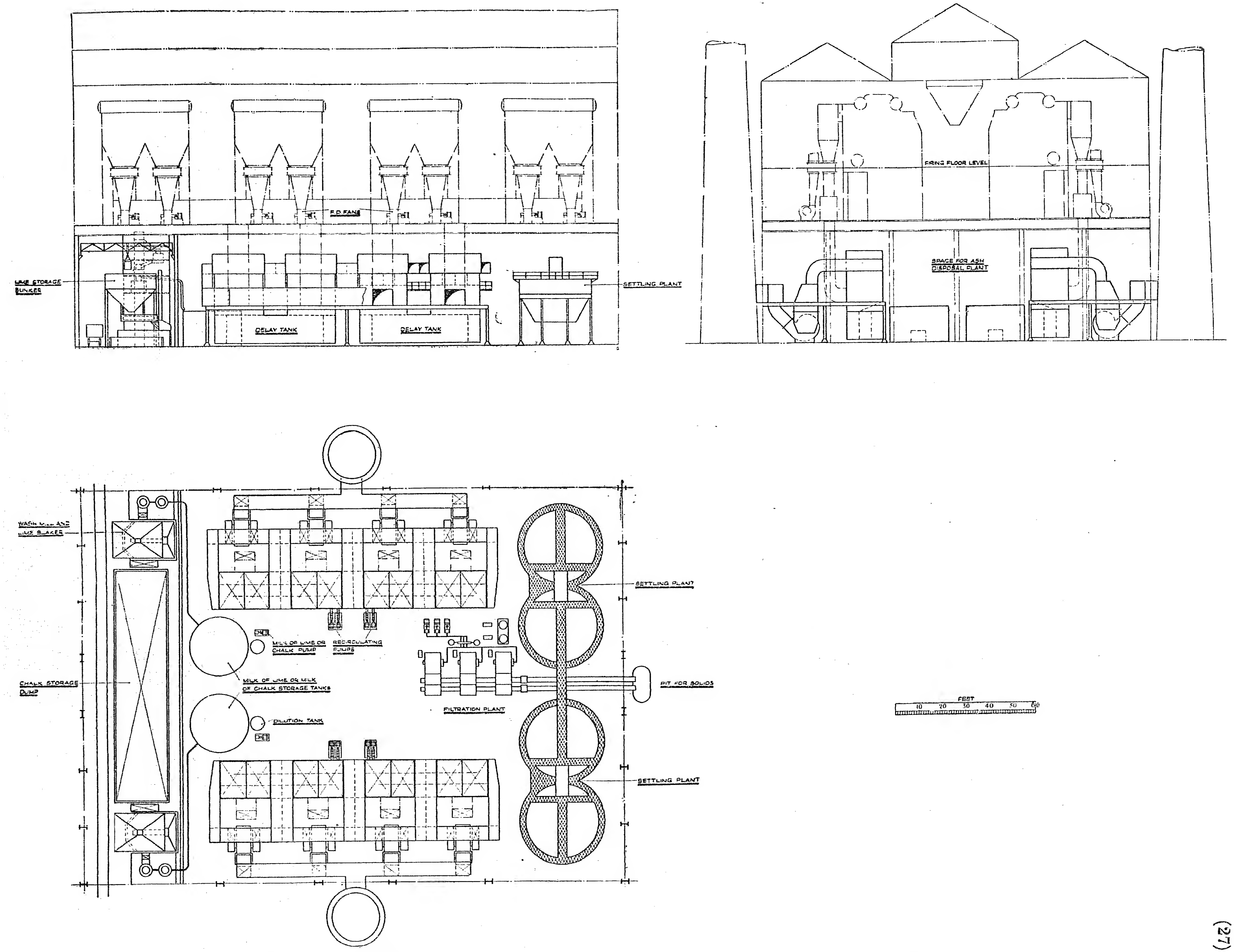


FIG. 16.—Lay-out of a central flue-gas scrubber system installed, complete with auxiliaries, in a boiler-house basement.

the scrubber is 5·4 grains per gallon. Hence, with 50 per cent oxidation, the delay time should be 2·4 minutes. As any increase in the oxidation increases the concentration of suspended calcium sulphate, and so increases the rate of crystallization, this delay time is sufficient.

(*l*) *Temperature of Circulating Liquor.*—The partial pressure of moisture in the flue gas from a typical Durham coal duff = 0·063 atm. at 13 per cent CO_2. With an inlet-gas temperature of 275° F. the exit temperature and temperature of the circulating water become 124° F.

(*m*) *Water lost by Evaporation.*—The increase in partial pressure of water in the gas is 0·065 atm.

Hence water evaporated on full load, galls. per min.	=21·8
or tons of water per ton of coal	=0·52

(*n*) *Final Volume of Flue Gas.*—The final volume of wet flue gas at 124° F. becomes 85 300 cub. ft. per min.

(*o*) *Extra Power Consumption by Induced-Draught Fans.*—If the induced-draught fans of the boiler are placed after the scrubber, this reduced gas volume is in most cases sufficient to compensate for the extra power consumed on account of the draught loss due to the insertion of the scrubber.

Thus, with the assumptions:—

Load factor, per cent	66
Chimney height above scrubber, ft.	200
Gas velocity in chimney, ft. per sec.	33
System resistance in boiler, in. water gauge	4·5
Draught loss in scrubber and associated ducts, in. water gauge	0·5
Overall efficiency of fan and motor, per cent	60

The extra power consumption per boiler is of the order of only 7 kW.

(*p*) *Settling and Filtration Plant.*—The surface area of efficient continuous settling plant required to remove 13 tons per hour of solids from a scrubber on powdered-fuel firing is approximately 3 000 sq. ft. This figure is based on running experience with a Boby conical settler (Andrews patent).

It is unnecessary and uneconomic to supply settling plant of sufficient area to produce a clear overflow, as this overflow is returned to the scrubber circulating system. The authors have found that a clarification efficiency of 70 per cent is sufficient, and in fact has the advantage that the smaller $CaSO_3$ and $CaSO_4$ particles are returned to the scrubber to grow larger.

The sludge discharged from the settler contains 33 to 40 per cent solids. This may be de-watered on a continuous rotary vacuum filter to 35–40 per cent H_2O. The filtration area required for 13 tons per hour dry solids is 500–700 sq. ft., depending on the design and speed of rotation of the filter drum. As already mentioned, continuous discharge centrifuges (page 16) may be installed instead of settlers and filters. The moisture content of the mud discharged from this type of apparatus is slightly higher at 48 per cent.

(*q*) *Total Make-up Water and Liquor Balance.*—With six boilers on full load, and with an average of 35 per cent moisture in the filtered rejected mud, the "make-up" of fresh water is as follows:—

	galls. per min.
Replacement of loss by evaporation	131
Replacement of loss with wet mud	25
Total make-up	156

or 0·62 ton of water per ton of coal fired.

	galls. per min.
Total purge to settling plant (70 per cent clarification) or approximately 2 tons of liquor per ton of coal fired	440
Total water required to prepare 7 per cent lime slurry	92
Make-up water to glands and "mixed" liquor tank	84

B. Control of Plant: Labour Required.

Unit System.—With a unit system of one scrubber to each boiler, no extra labour is required for operation of the scrubbing units. The lime addition can be controlled automatically from the pH recorder, or manually by the boiler operator. The only other control is that of the purge. In one system of operation an overflow purge pipe is fitted in the scrubber hopper (10 in Fig. 9) and the purge is controlled by the operator varying the amount of "mixed" liquor supply from the settling plant to the scrubber system, according to the reading of a density recorder indicating the proportion of suspended solids in the system. In such a system, the total clarified liquor from the settlers common to all the scrubbers is collected in a tank fitted with a make-up supply controlled by a ball valve (16 in Fig. 9). The control of the make-up supply is then automatic.

Periodical routine inspection is required of the scrubber head tank and hopper levels, while occasional sweeping with a wire broom will ensure that the liquor distribution nozzles in the scrubber head tank remain clear without interfering with the normal running of the plant. Generally speaking, these duties may be performed by the part-time services of a man occupied on general inspection of all boiler-house auxiliaries.

For a boiler plant of the size described in this flow sheet there are also required on the unit system two men per shift for operation of the settling and filtration plants, lime supply and return liquor pumps, or one man if centrifuges are installed instead of settlers and filters. The lime-unloading and slaking plant will also require two men on two or three shifts according to the design of the plant, the magnitude of the night load, and the size of the slurry stock tanks.

Central System.—With a central system, three men on shift will be sufficient to operate the whole of the plant owing to its greater compactness. Two men, as before, will devote most of their time to lime unloading, slaking, and storage, whilst the third will be concerned with the control of the whole of the scrubbing plant proper from a central control panel.

It is assumed that continuous lime slakers of modern design with modern unloading equipment are supplied in both the above plants.

Mud Disposal.—The mud rejected from the system is

moist and easy to handle. No extra labour is therefore required for the disposal plant above that required for disposal of the ash collected in alternative systems normally supplied for the dedusting on pulverized-fuel plants.

Staff Supervision.—Although the plant is primarily a chemical plant, introducing many new features to power-station engineers, they will have no more difficulty in controlling it than they have in the softening and conditioning of the boiler feed water. The extra plant involved in the scrubber will, however, require the part-time services of one chemist-manager for supervision.

C. Examples of Commercial Installations.

Three typical examples of lay-outs for commercial plants are illustrated in Figs. 14, 15, and 16, and two typical designs for scrubbing towers to be installed on the unit principle are shown in Figs. 12 and 13.

In Fig. 12 the scrubber consists of two nests of cells; each nest has two rows of three cells and each cell is 5 ft. 3 in. square. A plant incorporating four such scrubbers, each for a boiler of 200 000 lb. per hour evaporation, is now in course of erection. The following details of this particular design should be noted:—

(i) Inlet ducts on one side only of each nest of cells, the cells having a common hopper bottom, with a single liquor outlet, but with a division plate down the centre, the bottom edge of this division plate being submerged. This last feature, in conjunction with dampers in the gas inlet ducts, enables one nest to be opened up while the other half of the scrubber is running.

(ii) The very large gas space at entry within the scrubber, a feature making for good gas distribution, which in all cases is further ensured by the small but designed pressure-drop across the liquor distributors on the deep plates, or primary scrubbing elements.

(iii) Gas exit ducts on *both* sides of each nest of cells. This reduces the overall height of the scrubber and, consequently, the pumping costs.

(iv) The system of "vertical assembly" at the top of the scrubber, whereby, commencing at the top, each component can be lifted out in turn without undoing any bolted connections. This is a standardized feature.

(v) The quick-opening doors, one to each cell. These doors, which are fitted as standard, give immediate and complete access to the grid packing, which can be withdrawn and replaced quite easily—an arrangement contributing to ease of erection.

(vi) The simplicity of the large-capacity overflow, ensuring that in no circumstances can liquor get down the flue-gas uptake to the scrubber.

Fig. 13 shows a scrubber for a boiler of 250 000 lb. evaporation per hour. In this case each boiler scrubber consists of two separate scrubbing towers, each with its own delay tank. Each scrubbing tower consists of two nests of cells, each nest has two rows of three cells, and each cell is 4 ft. 6 in. square. This arrangement fitted in very well with the two Howden-Ljungström air pre-heaters per boiler. Gas entry and exit is on one side only of each nest of cells, a feature in this case largely dictated by the plant being required to conform to a building already designed and nearly erected. The further items to be noted are:—

(i) Vertical assembly, overflow arrangements, and quick-opening doors as for Fig. 12.

(ii) The pump arrangement, whereby either scrubbing tower can be run from either pump, and either pump can be dismantled with either or both scrubbing towers running (each pump being capable of delivering 50 per cent more than the maximum liquor rate required for one scrubbing tower).

(iii) The pumps are driven by variable-speed motors.

A minimum number of valves is used. These valves are of straight-through design; they are not used for throttling.

It will be readily appreciated that the system of cell construction adopted for the scrubbers not only enables the grid packing to be assembled in units of one or two grids easily handled, but also lends itself very readily to adaptation to the scrubber form or arrangement called for by any building or site requirements.

The three major possibilities with regard to complete plant lay-out are clearly exemplified in:—

(*a*) Fig. 14, as showing a unit system in which the scrubbing section is in the boiler house and the lime and solids separation sections are outside. This scheme, with its exaggerated emphasis of the division of the plant into three sections, contrasts strongly with

(*b*) Fig. 15, showing a compact central system in which the whole plant is outside the boiler house. This scheme offers the cheapest ensemble, pipe lines being reduced to a minimum and no parts being housed in a building. It will not be applicable, however, to many power stations in the larger towns, where site area is too valuable or too restricted to permit of horizontal spread. In such cases a central system can be put in the boiler house, as indicated in

(*c*) Fig. 16, where a central system installed in the boiler-house basement is shown. This scheme has a number of attractive features, practical and economical.

These three basic schemes permit of so many variations in arranging or combining the main three sectional components that it seems very unlikely that there can be any station, projected or erected, where the plant could not be installed.

Section VI.—CAPITAL COSTS AND RUNNING CHARGES.

A. Capital Costs.

The general economic problem of atmospheric pollution was dealt with in Section I. There now remains to be considered the narrower and more particular incidence of the economic problem, as affecting the actual figures of the costs and charges to be entered in the ledgers against power production.

No appropriate charges have, in the past, been entered on the debit side of these ledgers in respect of the material damage, loss in amenities, and injuries to health, which have been so irrationally overlooked in the past. That such charges, as book charges only, should have been entered or always borne in mind can be justified fully. The power-station administration and executive would then have been concerned with the savings they would effect, and not with the charges they would incur from the installation of adequate flue-gas cleaning plant,

whilst the community would have known the real costs of power production instead of the partial costs covered by the rates given in accounts for payment presented by the distributing companies. Admittedly, somewhat similar remarks apply with equal force to the other sources of industrial pollution, but, as indicated in Section I, the large point sources in urban areas must be dealt with first.

In arriving at estimates of the average capital costs, a flue-gas cleaning installation, for which the flow sheet was given in the previous section, will be considered. Such an installation would apply to a power station, of

(*a*) On the unit system, 8 scrubbing units, each of 350 sq. ft. cross-sectional area, and each complete with delay tank, re-circulating pumps, instruments, etc.

(*b*) On the central system, 6 scrubbing units, each 350 sq. ft. cross-sectional area and each complete as before.

In the former case the number of scrubbing units in commission at any time would be the same as the number of boilers in use. In the latter case five units would be sufficient for the maximum load on the boiler house, and there would always be at least one spare unit as a standby.

TABLE 5.

Capital Cost and Capital and Maintenance Charges for a Flue-gas Scrubbing Plant for 8 Boilers of 200 000 lb. per hour Evaporation.

	Unit system				Central system			
Total scrubber area .. .. Number of units	2 800 sq. ft. 8				2 100 sq. ft. 6			
	Capital cost	Capital charges at 10 per cent	Main-tenance	Main-tenance charges	Capital cost	Capital charges at 10 per cent	Main-tenance	Main-tenance charges
	£	£ per year	per cent	£ per year	£	£ per year	per cent	£ per year
1. *Scrubber,* including delay tank re-circulating pumps and pipes, flues, instruments	108 000	10 800	3	3 240	83 000	8 300	3	2 490
2. *Lime Plant,* including unloading plant, bunkers, slurry preparation stock tanks, and pumps ..	19 000	1 900	2	380	16 000	1 600	2	320
3. *Settling Plant,* including pumps and purge liquor piping	23 000	2 300	1	230	22 000	2 200	1	220
4. *Filtration Plant,* including pumps and piping	8 000	800	4	320	8 000	800	4	320
5. *Foundations* and miscellaneous charges incurred by power station. 5 per cent of capital cost ..	7 900	790	Nil	Nil	6 450	645	Nil	Nil
Totals	165 900	16 590		4 170	135 450	13 545		3 350

120 000 kW installed capacity and with 8 boilers of the size mentioned on page 29 of the 1932 Report of the Committee appointed by the Electricity Commissioners, and discussed in that Report under the heading of "Capital and Operating Costs." The authors have taken this size as being in accord with modern practice, and not for purposes of making any comparison with the cost figures given in the above Report. Clearly there could be no real basis for such a comparison, for the costs in the two cases appertain to widely divergent values.

The authors' estimates will be for the unit and central systems respectively shown in Figs. 14 and 15, the capital cost of the latter being appreciably less than that of the former. For the power station of the size now under consideration, there would be required:—

A comparison of the capital costs for the two systems is given in Table 5. For the figures given with the unit system, the scrubber has been debited with the cost of the short lengths of flue ducts leading from the air preheaters to the scrubbers, and from the scrubbers to the induced-draught fans; whereas for the central system it is assumed that the flue gases, in any case, would be carried by one or two central flues to one or two chimneys placed at the end or ends of the boiler house, and that consequently the scrubbing plant would be charged with the short lengths of duct additional only and adjacent to the chimneys.

In the above comparative figures it is assumed that the foundations for the scrubber structures of the central system and the cost of strengthening the boiler house

steelwork in the units system are equal, at 5 per cent of the capital cost of the whole plant.

The cost of applying the process to existing boiler plants is bound, in general, to be greater than the cost of installing the process in new power stations, even where the flue-gas cleaning plant must be accommodated in the boiler house, provided this latter is *from the first* considered as a home for the boilers and flue-gas cleaning plant, e.g. as in the case illustrated by Fig. 16.

(iii) *Lime.*—The load factor of the power station has been assumed to be 66 per cent (i.e. 66 per cent of 120 000 kW), and the alkali used has been taken as lime at £1 5s. per ton of 95 per cent CaO, a price that would probably rule in practice for the majority of power stations, although chalk may be cheaper in some instances and much cheaper in a few.

(iv) *Cost of Power.*—This has been taken at the basic rate of 0·2d. per kWh, as given in the list of graded tariffs charged by the Central Electricity Board; actually a lower unit charge should be taken, since for boiler auxiliaries of the kind in question power should be charged on a purely marginal basis—i.e. marginal for all the constituent items—but here the charge taken is of no great moment and the authors prefer to be consistent in giving conservative figures.

(v) *Labour.*—A figure of £3 per week per man has been taken, the labour requirements being generally as described in Section V B.

(vi) *Discard of Solids.*—No extra cost has been charged against mud disposal, since an urban power station will have to get rid of the ash in any case, irrespective of flue-gas cleaning; moreover, the methods of solids disposal will be multifarious.

So far as running charges are concerned, the central

TABLE 6.

Annual Operating Cost of Flue-gas Scrubbing for Power Plant of 120 000 kW Capacity.

Assumptions:

Turbine capacity	120 000 kW
Coal consumption	1·2 lb./kWh or 372 000 tons/year
Annual load factor	66 per cent
Pump efficiency	72 per cent
Fan efficiency	60 per cent
Motor efficiency	90 per cent
Charges for power	0·2d. per kWh
Cost of lime	£1·5 per ton

	Unit system		Central system	
	Particulars	Cost per annum	Particulars	Cost per annum
Cost of alkali (lime)	10 300 tons at 30s. per ton	£15 450	10 300 tons at 30s. per ton	£15 450
Power Consumption:	kWh	£	kWh	£
Re-circulating pumps (average)	490	3 570	490	3 570
Lime pumps	4	29	1	7
Make-up water	4	29	1	7
Return liquor	12	87	4	29
Filter plant	120	875	120	875
Induced-draught fans	42	310	42	310
Total power consumption	672 kWh	£4 900	658 kWh	£4 798
Overall power consumption per ton of coal fired, kWh	15·8 kWh	—	15·5 kWh	—
Labour Cost:				
Scrubber, etc.	$\frac{1}{3}$ man on 3 shifts	2 030	3 men on each of 3 shifts	1 400
Settling and filtration	2 men on 3 shifts			
Lime plant	2 men on 3 shifts			
Contribution:				
Chemist and instrument supervisor	(part time)	250	—	250
Total operating cost		£22 630		£21 898

B. RUNNING CHARGES.

In arriving at the figures for the various items in the running charges, as shown in Tables 5 and 6, the criteria taken into account were as follows:—

(i) *Capital Charges.*—These were taken as 10 per cent throughout, a reasonable figure, conforming with that in the 1932 Report of the Committee appointed by the Electricity Commissioners.* (Table 5.)

(ii) *Maintenance.*—A percentage of the initial capital cost has been taken as the annual maintenance rate, the percentage varying with the different sections of the plant in accordance with the nature of the apparatus in the particular section and as based on experience from analogous uses of similar apparatus—a conservative figure throughout being preferred. (Table 5.)

* See Reference (1).

system has a gradually accumulative advantage from items fixed as a percentage of initial capital outlay, and covering labour and power consumption. Lime consumption in both cases must be the same.

It is to be noted that the cost of alkali in London, using chalk at 8s. per ton (delivered by water), is equivalent to using lime at only 25s. per ton. This estimate is based on the use of 35 per cent excess of crude chalk containing about 20 per cent moisture.

In Table 7 are summarized the running charges for the two systems, as annual charges and as pence per kWh.

TABLE 7.

Summary of Total Annual Costs of Flue-gas Scrubbing Plant for Power Plants of 120 000 kW Capacity.

Load factor = 66 per cent.
Coal consumption per year = 372 000 tons.
Total power generated per year = 695×10^6 kWh.

Charges	Unit system		Central system	
	£ per year	Pence per kWh	£ per year	Pence per kWh
Capital	16 590	0·0058	13 545	0·0047
Maintenance ..	4 170	0·0014	3 350	0·0012
Lime	15 450	0·0053	15 450	0·0053
Power	4 900	0·0017	4 798	0·0016
Labour	2 280	0·0008	1 650	0·0006
Total ..	43 390	0·0150	38 793	0·0134

C. SUMMARY OF COSTS.

Summarizing the above, it is seen that the process of complete flue-gas cleaning costs:—

(i) *In initial outlay*:—
  (*a*) £1·4 per kW installed for a unit system;
  (*b*) £1·1 per kW installed for a central system.

(ii) *In running charges*:—
  (*a*) 0·0150d. per kWh for a unit system;
  (*b*) 0·0134d. per kWh for a central system.

To the power-station engineer these costs may seem appreciable, but they are negligible compared with the price paid by the private consumer. They also compare very favourably with the costs of transmitting power from a power station situated in the open country 10 miles from the centre of a large urban load. Thus in London and other large urban areas the cost of transmission over such a distance is generally estimated to be at least 0·02d. per kWh.*

Considered on a coal basis the cost of complete flue-gas cleaning is equivalent to 2s. 1d. to 2s. 4d. per ton of coal fired. This is small compared with the "cost" to the community of not cleaning the flue gases, as estimated on any reasonable basis:†

* See Reference (7).

† *Ibid.*, (8).

Section VII.—CONCLUSIONS.

The authors regret that, owing to the exigencies necessarily associated with presentation in a single paper, they have not been able to include all the subject matter desirable and that, even with that included, discussion in many cases has had to be curtailed. Doubtless the present paper could have been expanded with some ease and resulting benefit into at least half a dozen papers, each dealing with matters of importance, and of some obscurity.

The authors trust, however, that in their attempts to present a paper which would be self-contained, inasmuch as all the important phases of the subject matter would be brought together, they have omitted nothing of major importance and have maintained a reasonable balance in their methods of presentation.

While the "supersaturation" side of the process developed for flue-gas cleaning may be of great interest and appeal to the chemist, what is likely to appeal most to the engineer is the extremely small "scrubbing volume" which has been used to give such a high performance with a very small pressure-drop, and which constitutes but a minor fraction of the total volume of the scrubber. The grid packing, in the form adopted to meet the specific requirements described in Section I F, is a contributory factor to the high performance, but there are other factors, some of which are of equal importance, e.g. liquor distribution, liquor spread, liquor rate, and gas rate.

The grid-packed scrubber, as described, may be used for the removal of fine dust from any gas permitting a wet process to be used. It is being used, for example, for the removal of a fine soluble dust from the exit gases of a rotary salt drier working on fertilizers, the gas and liquor flows in this case being counter-current, for ease of installation. Practically the same apparatus that is being used for cleaning boiler flue gases can be used for cleaning cement kiln gases, the alkali consumption then being negligible owing to the lime and chalk content of the dust. The pilot plant has now been transferred for trial on this duty. Another application is the removal of dust from blast-furnace gases, where removal of the excess water vapour in the cleaned gas may be readily effected by cooling to atmospheric temperature, a process which will result in an even greater diminution of the dust content of the gas.

ACKNOWLEDGMENTS.

During the progress of the work described in this paper, the authors have had the opportunity of frequent consultations with Messrs. Preece, Cardew, and Rider, on the problems involved in connection with the sulphur extraction plant now being erected for the Swansea Corporation, and also with Dr. R. Lessing. They were enabled to compare notes with them during the development of the work on both the chemical and engineering side, and they wish to express their thanks to both parties. In particular they are obliged to Dr. Lessing for supplying information on the rates of de-supersaturation of calcium sulphate solutions and for permission to reproduce Fig. 4.

The authors' thanks are also due to Messrs. William

Boby and Co., Ltd., for the loan of the small settler used with the pilot plant.

Their thanks are also due to many of their colleagues for co-operation and assistance in the development of the process described and in the preparation of this paper. In particular, their thanks are due to Mr. H. S. Sayles, who has been associated with the engineering side of the experimental work from its inception; to Mr. C. H. Bosanquet for a survey of eddy diffusion, and for his help in the preparation of Fig. 1; to Messrs. W. J. Clark and R. A. Bell for their help in developing the "all-mains" pH recorder; and to Messrs. E. W. Batten, J. G. Lewis, E. McCulloch, and Miss D. Freeman, for their assistance in the detail work of the investigation.

Finally, the authors' thanks are due to the directors of Messrs. I.C.I. (Fertilizer and Synthetic Products), Ltd., and of Messrs. James Howden and Co. (Land), Ltd., for permission to publish this paper.

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(7) Compare statement by Electricity Commissioners with reference to the application made by the Borough Council of Fulham for the consent to the extension of Fulham power station.

(8) Compare figures given in SHAW and OWENS [Ref. (4) above, p. 57], and in *Economist*, 1934, vol. 119, p. 913.

DISCUSSION AT A JOINT MEETING OF THE INSTITUTION OF ELECTRICAL ENGINEERS AND THE INSTITUTE OF FUEL, 17TH JANUARY, 1935.

Prof. W. M. Thornton: The problem dealt with by the paper is at least 400 years old. It began in Queen Elizabeth's time, when objection was taken to fumes from coal brought by sea from the Tyne into London. The matter has been brought to a head by the immense increase in the concentration of combustion in modern boiler-houses.

The paper indicates that Newcastle has the worst record in regard to atmospheric pollution. That was entirely due to a power house with a chimney of insufficient dimensions, which just lifted the dust and dropped it on to a neighbouring area. The power house in question, however, is no longer there.

Once a solution is found of the smoke problem it will stand for all time. The paper aims at giving such a unique solution.

Sir Leonard Pearce: The authors begin their paper by taking us back to 1927 when, for the first time, a definite obligation was placed on a supply company to adopt means for removing the oxides of sulphur from the flue gases. This innovation, however, was not promoted by the reasons given in the paper so much as by the unfortunate publicity given to the litigation in connection with a well-known power station in the North. The year 1927 therefore marked a turning point in connection with the treatment of flue gases as a feature of power-station design; the London Power Co. were compelled to commence a series of researches, which were begun on a small plant, extended to a larger plant at their Grove Road station, and continued elsewhere. The particulars of these researches and the results ultimately secured at Grove Road and Battersea were embodied in the two technical papers referred to by the authors, in three Government White Papers, and in numerous technical articles. The final experimental plant at the Grove Road station dealt with gases from a boiler burning some $3\frac{1}{2}$ tons of coal per hour, against the $\frac{1}{2}$ ton per hour on the pilot or experimental plant of the authors. Only so far as the authors appear to invite references to the Battersea plant, or directly or indirectly to draw comparisons between an effluent and a non-effluent system, do I propose to make specific mention of the Battersea plant. I assume that most engineers know all about it. The solution of the problem of flue-gas washing is therefore of recent origin, and, as the authors point out, the first patent for a comprehensive plant was taken out in 1929 by the London Power Co.

The theme of Section (1) of the paper is: (*a*) That gas-washing plants are necessary in modern power stations owing to the emission of dust and acid gases, which have a deleterious effect on human life, vegetation, and the fabric of buildings. (*b*) That the recommendations given in the report of the committee appointed by the Electricity Commissioners to consider grit emission from power stations, and in particular the recommendation contained in that report in relation to the height of station chimneys, are of little or no value in the matter of dust and acid emission. The authors very properly point out that the latter question does not come within the terms of the reference of the committee. Support for (*a*) is sensibly growing, but as regards (*b*) I shall be interested to hear what sort of reception is given to the authors' somewhat dogmatic assertion that high chimneys offer no solution to the problem. I venture to think that this conclusion will be very unpopular. The authors' line of reasoning is that the emission of dust and acid gases follows the laws of diffusion, and is not governed by the weight of particles causing them to fall to earth. From the purely practical point of view it would appear that the deposition of the dust and acid gases is largely governed

by such factors as the direction of the wind, down draught, and general atmospheric conditions; and that fundamentally—other things being equal—it is clearly an advantage to have as high chimneys as possible. No doubt the authors' curves based on a steady wind velocity of $11\frac{1}{2}$ m.p.h. and assuming no other disturbances are perfectly correct, but anyone who has spent a considerable length of time in the vicinity of a power station will readily agree with an observation of the authors as to the sensitiveness of the human organs to minute concentrations of SO_2. Even under similar load conditions at the station, and burning similar types of coal, the proportion of sulphur noticed at ground level can vary owing to weather conditions. I therefore suggest the possibility of attaching too much importance to theoretical mathematical calculations, which may tend to be of more academic than practical significance.

Many engineers are impressed with the possibilities of an all-alkali non-effluent process, and some extensive researches on this subject have been carried out at the Grove Road station; but the authors' suggestion that some form of wet washing leads necessarily to the admission that the type of flue-gas washing to be adopted should not have any discharge into rivers or streams, appears to be an over-statement of the case. In this matter we are concerned with two sets of conditions: (1) in which there is an ample river water supply available to the power station, making it permissible for a suitably treated effluent to be discharged into the river (the difficulty attendant upon accomplishing this has been solved by the London Power Co. to the satisfaction of the authorities); and (2) those stations where no such ample supply of water is available. It by no means follows that a system designed for the latter condition is necessarily the best when the former condition obtains. The effluent and the non-effluent systems each have their merits, but it is essential that the fields of application should not be confused. The authors' system may be capable of universal application, but it does not necessarily follow that it is universally desirable to make use of this system.

As to the effluent discharge to rivers, the authors make much of the restrictions at present applied by the authorities and suggest that in the future these restrictions will become prohibitions, thus forcing stations to use a non-effluent process. Again, in advancing the claims of their system the authors refer to the possibility of river pollution. I must, however, combat any suggestion that an effluent system must necessarily pollute a river, and in support of this claim I should like to quote the following extract from the Third White Paper.

" It will be remembered that the Port of London Authority laid down rules for the condition of the water passed back into the Thames after being used for cooling and for processes of sulphur elimination. These required that the quantity of suspended matter should not be increased in transit through the station, nor should the Thames water be rendered acid, nor contain more than 14 grains in 100 gallons of de-oxygenating matter (including sulphite) more than it had originally.

" Through the courtesy of Sir David Owen, of the Port of London Authority, we are able to give the opinion of Dr. J. F. Beale, who surveys the river for that Authority. He expresses his appreciation of the expense and trouble given by the London Power Co. to solve this problem and states that there is no appreciable increase in the suspended matter, that the de-oxygenating matter added is well within the statutory limit and that the water has not been rendered acid."

I should like to refer to Table 1, and supply the missing figure relating to the percentage of dust removed from the Battersea plant. The White Paper states: " Attempts to determine the solid matter in the washed chimney gases have so far failed to give any measurable quantity "; presumably this means that the solid-matter content is nil. The figure of 90 per cent sulphur elimination given in Table 1 for the Battersea station has been substantially improved upon; the average for the last completed year, when more than a quarter of a million tons of coal were burned and the alkali used averaged 10 lb. of chalk per ton of coal, did not fall below 90 per cent. The best sulphur-elimination figures obtainable from the plant, and consistently maintained, have been of the order of 98–98·5 per cent.

The description of the authors' plant and of the results obtained contains a few statements with which I cannot altogether agree, such as (*a*) that this is the first time a really efficient scrubber has been employed on a gas-washing process; (*b*) that the non-effluent system gives a greater flexibility than any other type of wet washing plant; and (*c*) that all other wet washing plants require a constant water rate at all loads. This latter statement was quite disproved by the results at Battersea, where coal consumptions have averaged from 20 to 70 tons per hour with a corresponding reduction in water and alkali quantities, both water and alkali being under complete control. So far as my experience goes, two of the main difficulties associated with the effective operation of a non-effluent process are (*a*) the difficulty of accurate control of the amount of reagent required, and (*b*) the serious possibilities of choking of the scrubber absorbing tower. The authors claim to have definitely overcome these difficulties, and so far as their pilot plant is concerned this claim seems to be abundantly substantiated. As I have already pointed out, however, the experimental plant at Billingham is a small one utilizing only about $\frac{1}{2}$ ton of coal per hour, and it is necessary to treat the evolution of a full-sized plant with some reserve when its design has been based on such a relatively small plant. At the same time I am impressed by the authors' ingenious conception of a delay tank for removing the supersaturated sulphites and sulphates outside the scrubber. The problem of liquor treatment as directed to the prevention of scaling is quite the most vital part of the process, and its successful solution by the method outlined in the paper must be regarded as a high achievement. The method, however, appears to set a definite limit to the flexibility of the process. What the authors term " the back potential of the scrubbing surface " only exists as long as that surface is quite free from scale. Any temporary error of operation, or an uncontrollable increase of the mass rate of SO_2 passing to the scrubber, may well produce a slight deposit. The non-isomorphic nature of the scrubber surface will then be destroyed, and scaling will

proceed with normal rapidity. This point is evidently clearly recognized by the authors, and it emphasizes the necessity for close and constant supervision of the gas and liquor rates. This difficulty seems to be inherent in all slurry processes, and I feel convinced that the effective running of such a plant as the authors have described, with a limited amount of scientific control, is not such a simple matter as they suggest. Indeed, the necessity for avoiding mal-operation is stressed again and again in the paper.

With regard to the choice of an alkali reagent, it is interesting to note that the recent prevailing drought so altered the constitution of Thames water that scale was formed on the Battersea scrubbers when lime was used as a final washing. The use of ground Kent chalk in place of lime not only solved this problem but brought about the removal of every trace of scale which had been deposited by the lime. Soda ash, as well as lime and chalk, were used on the first experimental plant and also on the full-scale plants at Grove Road and Battersea, and the decision has been arrived at that from every point of view ground Kent chalk is best. It is quite as reactive as lime in full-scale operation, and satisfactory elimination results have been obtained over a long period when using about 10 lb. of chalk per ton of coal, at a cost of 1·1d. per ton of coal fired, with chalk at 20s. per ton.

The various ratios and design figures given in Section (5) of the paper enable a reasonable comparison to be made between the authors' typical 120 000-kW power station and the Battersea plant, which is of approximately the same size. From this section of the paper I deduce that the area required in the authors' process for the wooden scrubbers is practically identical with that provided for the wooden scrubbers in the chimney tower uptakes at Battersea. This is an interesting result, seeing that the problem was approached from somewhat different angles in the two cases.

On the other hand, the liquor quantity required per minute for the authors' process shows an enormous increase over the corresponding figure for Battersea, namely, in the ratio of 9: 1: hence the necessity for very low pump heads in their case. From a perusal of some of the typical lay-outs shown towards the end of the paper I gather that this most desirable condition is not always capable of realization. An approximate calculation shows that, with the non-effluent process, the pumping power will be well over 50 per cent in excess of the Battersea figures, even after allowing for the greatly increased pumping head at Battersea.

The authors gloss over and seriously minimize the cost of effluent disposal with their system. The effluent will consist of a wet mud which, if dried, will amount to approximately one-fifth of the weight of coal fired. The mud will contain at least 40 per cent of water, so that the total weight of mud will be nearly 30 per cent of the weight of coal burned. For a power station burning, say, 6 000 tons of coal per week, it appears that something like 2 000 tons of wet mud must be removed and dumped weekly; this is the problem which the authors dismiss with the words (page 28) "The mud rejected from the system is moist and easy to handle. No extra labour is therefore required for the disposal plant above that required for disposal of the ash collected in alternative systems normally supplied for the dedusting on pulverized-fuel plants." Nor do the authors include, so far as I can see, in their estimates of the running costs, any allowance for the disposal of the wet mud. In the case of the Battersea system—again on a more or less comparable basis—the average weight of sludge produced does not exceed 60 tons per week, of which some 80 per cent represents Thames mud. The cost of removal (£15 per week) is entirely balanced by the sum received from the sale of ashes. From the known figures for Battersea, and from the estimated figures given in the paper, there seems little doubt that the cost of the non-effluent system will be higher than the cost of the Battersea system.

The inclusive capital cost per kW installed at Battersea is £1·21, which is in very close agreement with the authors' estimated figure for their unit system. The comparison, however, is not a strictly accurate one because, in the figure for Battersea, the bulk of the building and civil engineering work appertaining to the flues, towers, and chimneys, is included; but so far as I can see this has no counterpart in the detailed capital estimates given by the authors in Table 5. It therefore seems reasonable to infer that on the basis of capital costs an effluent system will work out substantially cheaper than a non-effluent system. On the score of running costs there is no question which is the cheaper, because the figure for Battersea for the whole of the year 1934 works out at 0·005d. per unit, which is substantially less than the figure given by the authors for their system. It appears, therefore, that the overall charge—whether expressed in pence per unit generated or per ton of coal burned—must be appreciably less in the case of an effluent system than with the non-effluent system.

The electricity supply industry has waited some time for, and is now entitled to receive, some authoritative pronouncement on the policy of installing flue-gas washing plants. Is there to be any uniformity of action in the future: are certain stations to be compelled to install such plants while others are allowed to do nothing? If an authoritative pronouncement is made in favour of putting in these plants, there should also be a corresponding pronouncement on the standard of elimination expected. It would be regrettable if the Government were to be advised that it is necessary to reduce the amount of sulphur in the effluent gases below, or even down to, a figure representing 90 per cent elimination. Such a figure constitutes a burden of a very substantial amount on any undertaking.

Dr. H. A. Des Voeux: Ever since I first came to live in London I have been interested in the question of smoke in the atmosphere. The improvement in the London atmosphere which has taken place since those early days has been due almost entirely to the work done by the Coal Smoke Abatement Society, which I and a few others—none of us scientific men—helped to form in the year 1899. We only made about 13 converts in 3 years. Fortunately our propaganda is now spreading, and we now have the scientific world at our back. When we first discussed this question we gave no consideration to the presence of sulphur in smoke. When I asked my friends in the scientific world about sulphur in coal,

most of them said "I did not know there was any." That was the scientific attitude 30 years ago. Sulphur in the atmosphere is now a commonplace. It is a great pleasure to me to feel that engineers are now tackling not only the domestic side of the question but also the more difficult problem of the smoke emitted by big power stations. As regards the domestic side, low-temperature semi-coke for the open grate is very nearly a satisfactory solution of the problem.

I am interested in the use of chalk for the elimination of sulphur. I live in the New Forest, and have my own well. After I had lived there 2 or 3 years my hot-water pipes began to be blocked up with red scale, so much so that I had to put in copper pipes. I was told that this was due to the iron in the water, and I therefore had the water analysed by several different chemists, who reported that it contained only a minute trace of iron. At last I found a chemist who said to me: "It is not the iron that is blocking your pipes; it is the carbonic acid in your water." He made me an elaborate apparatus to get rid of this carbonic acid, but it would not work. Then Sir Alexander Houston, of the Metropolitan Water Board, said to me: "I advise you to put a little chalk in your well after you have pumped it." I followed his advice, and in a fortnight's time the scale in my hot-water pipes disappeared.

Dr. R. Lessing: The amount of the sulphur emission over London in terms of sulphuric acid is 1 000 tons per day, and the bulk of this comes from domestic chimneys and small factory chimneys. The outcry which precipitated the adoption of sulphur-eliminating plants in power stations some 5 years ago was hardly justified; in fact, the work which has been done at Battersea, and the work which is foreshadowed in the present paper, indicates that the centralization of sulphur emission—so far from adding to the acid pollution of the atmosphere—is in fact the means of dealing with it in the one and only practical and comprehensive way. I go so far as to say that the domestic chimney and the smaller factory chimney stand in the same relation to the large power-station chimney which is attached to an efficient sulphur-elimination process as does the cesspool to the well-run sewage works of to-day.

The future will probably see greater centralization of that portion of our energy supply which is not amenable to treatment beforehand, so as to avoid its contamination of the atmosphere. In this connection, I cannot see eye to eye with the authors in their statement that the pretreatment of the coal in regard to sulphur removal is not practicable. It is perfectly true that all the sulphur cannot be removed from the coal, but it is equally true that sulphur elimination is a linear function of the amount of sulphur there is in the coal to be burnt, and therefore depends entirely on the total input of sulphur in the coal and not on the percentage of sulphur in any unit of coal. From that point of view a great deal of expense and trouble will be saved, and the plant itself will be reduced in dimensions and in operating costs, if everything is done to procure as low a sulphur content in coal as possible.

The authors have proved that, as far as the removal of the sulphur acids and the incidental minor acid constituents of the flue gases are concerned, the only process that can possibly come into consideration is a wet washing process. It so happens that a wet washing process which is effective in removing practically all, and certainly 98 per cent, of the sulphur-oxides content of the flue gases is *ipso facto* sufficient to deal with the whole of the grit and dust. That portion of the problem therefore takes care of itself, provided that the sulphur oxides are extracted. It is practically an accepted fact to-day that a wet process must be adopted for flue-gas cleaning, and this raises the vital question of the effluent which is produced by such a process. Dr. Pearce has already given us a very clear statement of the factors which govern the choice of the system. His company was in the happy position of being first in the field, and therefore had practically the whole river to draw upon. In 1930 I pointed out* that, taking the case of London and the River Thames, a power station of the magnitude of Battersea, burning when completed 2 000 tons per day, would not find sufficient neutralizing agent (i.e. calcium carbonate) in the river at a time of severe drought such as we suffered from in the summers of 1929 and 1934. If more than one power station of that size were erected it would be practically impossible to take the risk of depending on the water alone. When the question of flue-gas cleaning was first mooted it soon became obvious that water alone, without the addition of a neutralizing agent, was entirely out of the question. Under the rather stringent conditions imposed by the Port of London Authority it became difficult to decide between an open-cycle (or effluent) process and a non-effluent process. Dr. Pearce and his colleagues had the courage to decide on the open-cycle process, knowing full well the very severe conditions which they had to fulfil. When I was asked in 1930 to advise on a decision by the Fulham authorities as to whether they should adopt an open or a closed cycle, I considered discretion the better part of valour and decided on the closed-cycle process rather than risk infringing conditions imposed by the river authorities. The moment the non-effluent cycle was decided on it became evident that an alkaline process, or one employing a neutralizing agent, must be adopted; and the experimental plant built at Fulham demonstrated very quickly that little difficulty arose from the sulphur extraction. It was proved that efficiency figures of 96 or 98 per cent offered no difficulties, provided one could either rely on a sufficiently large plant or else provide that type of plant which gave within its capacity an adequate scrubbing surface.

It had been practically decided to proceed on these lines when it became evident that continued re-circulation of a liquor charged with lime or chalk (I agree with Dr. Pearce in his preference for chalk) caused very serious scaling. During the early days of the working of that plant, within a space of 72 hours a deposit was obtained 2–3 in. thick in places. It then became evident that this question of scaling had to be investigated more thoroughly. Although we had to deal with materials (e.g. calcium sulphate) the chemistry of which was supposed to have been known for generations, no knowledge was available at that time of the particular behaviour of these very simple substances under the

* *Transactions of the World Power Conference*, 1930, vol. 4, p. 174; also *Fuel in Science and Practice*, 1930, vol. 9, p. 348.

conditions which were applied to them. It was then found that the whole difficulty could be solved by keeping supersaturation within bounds, in the way described by the authors. This could be done once the conditions of saturation and de-supersaturation had been finally established; Fig. 9 shows only the beginning of the work. It was later found that by adding a sufficiently large quantity of solid calcium sulphate to the liquors (up to 25 times the normal solubility of the salt) all the difficulties were solved. Under these conditions it is possible to circulate in the liquor up to 20 per cent of solid matter without any scaling whatever, and to compress an enormous surface into a relatively small total volume, knowing full well that the narrow passages which then exist will remain clear practically indefinitely.

I do not agree with the authors that the recovery of by-products is not advisable. All those who are engaged on sulphur extraction regard this process as a financial charge on the general working. Industrial development throughout the ages has shown that wherever there is such a charge, and wherever it is a case of a product being made as a waste product, some use for it will be found sooner or later. I fully agree with the authors that the mud which they describe as typical—a mixture of calcium sulphate, calcium sulphite, and flue dust, with its requisite quota of water—is not a marketable commodity. On the other hand, the fact that the supersaturation of the calcium-sulphate solutions can be satisfactorily dealt with has made it possible to reverse the original policy of trying to avoid the formation of this salt and make as much calcium sulphite as possible. The recognition that calcium sulphate is really no danger has made it possible to arrange for practically complete oxidation of the calcium sulphite, thereby making a uniform product, and one which certainly has, or should have, a fair market value. The addition of arrangements for providing complete oxidation does not add materially to the expense. On the other hand, it permits the running of a uniform waste product from the plant, with all the attendant advantages of having to look after only one kind of material instead of a number in varying ratios.

Mr. W. M. Selvey: What the authors have done is to work out successfully a process for cleaning very large quantities of very slightly contaminated gases. They have found a way of controlling when and where the saturation and precipitation shall occur. In the casual way in which many re-circulation processes are dealt with it has been very difficult to prevent the organs of re-circulation becoming at the same time the seats of crystallization. The factors with which the authors have had to deal are (*a*) the necessity for circulating large quantities of fluid, (*b*) time, and (*c*) the extent of the wetted area. Is their system really a non-effluent process? If we define an effluent as something which has to flow into a river, the authors' arrangement may be called "non-effluent." It recovers the sulphur in the form of a solid, but everything else which is soluble must still be discharged somewhere. The effluent consists of a clear solution of non-active soluble salts.

I regret that the authors should have included smoke-abatement propaganda in their paper. The electrical power industry has been responsible for a good deal of practical smoke-abatement by setting a standard of almost smokeless combustion, eliminating grit and dust from flue gases, and providing cheap power for water and space heating. I consider that it is very unjust to tack on to the electrical power industry all the propaganda which has gone on, principally and justly based on the open fire. By providing cheap generation, by making stations bigger, we have now brought the use of electricity into a very humble stratum of society. The authors suggest that raising the generating price of electricity by 7 or 8 per cent is not a matter of moment now. I am strongly opposed to such a comparison with the values conserved, suggested under the present circumstances of widely unrestricted smoke emission.

The authors showed a photograph of a smoky chimney; I take it that the smoke was produced by minimizing the flow of air through a pulverized-fuel furnace. I want to make a very important point in this connection. Such smoke as would be emitted from the Battersea station, were the flue-gas washing equipment not installed there, would be very difficult to detect. It would be of a faint grey, the discoloration of the gases being due entirely to solid particles. It is a curious fact that with power-station boilers, particularly pulverized-fuel boilers, if one deliberately makes smoke by cutting down the air supply, all the particles of coal which have been through the furnace are entirely coked. In the so-called black smoke which results I have not found the slightest trace of oil and tar. What smoke-abatement advocates most object to is really smoke containing oil and tar. I have made many experiments with various forms of washing apparatus, and I have never yet found a system capable of removing oily matter which water will not wet. This being so, whether propaganda about smoke-abatement has any marked relation to power stations is very much open to question.

Lieut.-Col. K. Edgcumbe: The authors show the value of a systematic study of the local distribution and concentration of sulphur and other impurities introduced into the atmosphere by the flue gases, but they also point out the difficulty and complexity of such measurements as at present made. I think, therefore, that a description of a very simple method which has been developed and tried out during the last 12 months by Mr. W. P. Digby may be of interest. The simplicity of the method is such that it would appear to be well worth further study.

Briefly, it consists in exposing a polished metal test plate to the atmosphere for a given length of time and determining the corrosiveness of that atmosphere by measuring the amount of surface tarnishing which has taken place. The tarnishing is measured on a direct-reading photo-electric photometer, the scale of which is graduated in percentages, as compared with a standard non-tarnished plate. An obvious advantage of the method lies in the fact that no sampling apparatus is required beyond a number of polished metal plates, so that a very large number of "samples" can be obtained at little expense.

The most suitable metal for the test plates appears to be either silver or the eutectic mixture of copper and silver. The plates are some 4 in. square and are exposed without protection.

As showing the order of reduction in reflecting power which is to be expected, I may say that an exposure of 24 hours in Westminster gave a 4 per cent reduction in August last, whilst the corresponding figure in October was 40·5 per cent, and in November as much as 47 per cent, the large increase being presumably due to the greater fuel consumption as well as the higher moisture content of the atmosphere in the autumn months.

As an example of the consistency to be expected from the method, five plates exposed simultaneously for a period of 6 days in Stockton-on-Tees showed percentages of 72, 70·5, 70·5, 70·7, and 71 respectively.

The method is equally applicable to measurements in the flue gases themselves, the exposure being much shortened. For example, an exposure of 75 minutes in the flue of a coke-burning stove showed a reduction of 42 per cent, which increased to 62½ per cent in a further 75 minutes.

Mr. Charles Erith: Few engineers will share the enthusiasm of the authors for the heavy addition to working costs (equivalent to about 2s. 6d. per ton of coal burnt in power stations) required to arrest sulphur in flue gases by chemical treatment.

As Table 1 shows, no chemical treatment is required for dust removal. Dust is almost completely eliminated in dry condition by electrostatic precipitators, or in wet condition by water washers, as used, for instance, on the power plant of Imperial Chemical Industries at Billingham; such washers also give partial removal of sulphur.

At present the only power station in the world eliminating sulphur from flue gases by chemical treatment is the Battersea plant of the London Power Co., which is equipped with nine large boilers. The extra capital outlay involved by the washing equipment was no less than £246 400; the additional working cost has not been disclosed, but the report by Dr. Pearce and others shows that in all essentials it was disclosed by their 1929 patent (No. 334650). The latter comprises the features of lime plant for alkaline washing in scrubbers, for ozonizing and the use of catalytic agents for settling and filtration, for grabs to remove the solid residues deposited, and for optional re-circulation of the washing liquid. Their No. 28 boiler at Grove Road has a unit chemical washer, 123 ft. high, with 34 800 sq. ft. effective area of scrubbers. It was tested with soda-ash as well as with chalk and with lime. Grit arrestors are used, prior to the alkaline washing.

The Howden–I.C.I. system described in the present paper is also available in either the central or the unit type. Fig. 10 shows the experimental unit, which has one-twentieth of the capacity of one large boiler. It has recently been removed, after trials at Billingham, for use on cement-kiln gases elsewhere. Guarantees of 96 per cent dust and sulphur removal have been made for power plants under erection at Swansea and Fulham; Fig. 14 shows a unit scheme of capacity similar to that of the eight boilers for the Fulham station. Since in Table 5 a cost of £165 900 is given for eight boilers each having four-fifths of the Fulham capacity, the latter plant may be assumed to cost £200 000; and as the authors give a working cost equivalent to from 2s. 1d. to 2s. 4d. per ton of coal burnt (see page 32), plus the cost of removal of mud-residue from the filters, the penalty for placing a new power plant in the Central London area is evidently equal to at least 2s. 6d. per ton of coal burnt. At Swansea the coal cost is only 7s. per ton, as against 17s. for London.

There is no return whatever to the user for this heavy addition to the working costs of power production; and plants on much less costly sites (e.g. Deptford and Barking) supply electricity to the London area without any such complication and cost. Existing power plants in the Central London area are at present free from this serious liability; but as it is possible to excavate a deep basement to accommodate the chemical plant, without any enlargement of the site area, as shown in Fig. 16, this obligation may be extended to them at any time. A comparison with Fig. 14 shows how much unnecessary extra area is added when the chemical plant is placed outside. When there is a power station working on the system described in this paper, it will be very interesting to compare its results with those already obtained at Battersea.

At Battersea, a large volume of water is pumped for water-spraying, between the grit arrestors and the alkaline scrubbers, and this water flushes the filtered effluent to the river; but this is only a small addition to the water pumped to the condensers. Water-sprays are absent from the Howden–I.C.I. system. In both systems, however, the alkaline washing liquid can be re-circulated, and the mud-residue from the filters has to be dumped out at sea, or otherwise disposed of.

Despite the heavy liability for costly chemical treatment of flue gases in urban areas, political reasons may decide municipalities like Fulham to generate electricity within their own boundaries. The adoption of sites free from obligation for chemical treatment of flue gases is, however, obviously desirable. In all modern power plants the greatest care is taken to secure the highest possible percentage boiler efficiency, representing a saving of a few pence per ton of coal burnt; this is achieved, for instance, by air pre-heaters, which are thus an asset. The chemical treatment of flue gases, as described in the paper, on the other hand, is not an asset, but a heavy liability.

Mr. A. L. Fielding (*communicated*): The authors quite rightly qualify the efficiencies given in Table 1, and express doubt as to their accuracy. Anyone who has studied the question of measuring the efficiency of a dust arrestor will realize that the majority of the efficiencies in that table are probably not even an indication of the true state of affairs. It is more than possible that some of the values include soot-blowing periods, whilst others omit these. In order to emphasize the wide divergence of figures obtained on the same plant, I would mention one which was guaranteed to have a dust-collecting efficiency of 88 per cent. It was believed that the figure being obtained was nearer 50 per cent, but from the ash balance averaged over all normal loads it was found that a value of only 35 per cent could be shown.

The technique of testing must vary with the efficiency of a plant. Considering dust removal separately, it is clear that a plant which collects only about 50 per cent of the dust passing will require entirely different methods

of sampling from one which has an efficiency of 90 per cent or over. For the latter equipment, which I hope will in future be the rule rather than the exception, I commend to the notice of the authors a suggestion made by the late Prof. W. E. Gibbs, that a porcelain rod smeared with petroleum jelly (with a drip point well above that of the flue temperature) be used to explore the flue at a point after the arrestor. After a definite time the rod is withdrawn and the amount of adhering deposit ascertained. Prof. Gibbs stated that frequently after tests on his experimental plant he found that it was merely a question of degree of discoloration, the weight of the deposit being so small as to be almost immeasurable.

For plants with efficiencies below 90 per cent it is agreed that the nature of the dust, as determined by the air elutriator, is as important as the quantity emitted. I suggest, therefore, that the true efficiency of a dust-arresting plant might be given as (Measured efficiency) × (Elutriator grade coefficient). The coefficient would necessarily have to be determined by experiment or evolved mathematically.

In Section (5) the authors are rather too optimistic as to the accuracy of their deductions, based as they are on a plant of limited size. Local conditions will have a tremendous influence on many of the values. For example, not the least important is the microscopic structure of the ash; upon this will depend its degree of adhesiveness, and naturally the water quantity. This is one of the most uncertain factors of wet gas cleaning.

Prof. Gibbs made a suggestion some time ago that oil might be used as the arresting medium. I should be interested to learn whether the authors have considered this idea. No doubt there would be many difficulties to be overcome before it could be adopted, but there is always a possibility of using a suitable oil which would give the residue a marketable value. The mixture might easily form the base of a waterproofing filler or a road material. This, however, could only be determined after very careful consideration of all the factors. Should such a scheme ever become practicable, the present concern at high fluid consumption would certainly be eliminated.

In regard to the authors' remarks on high chimneys, I should like to make reference to the behaviour of cement dust. During the discussion on a paper entitled "Collecting the Dust from Chimneys of Powdered-Fuel Installations,"* read in the United States in 1928, a speaker referred to a high stack that had been erected for a cement-making plant with the idea of obviating dust complaints. After the stack had been put into operation a man who lived about 3 miles away began to call regularly with a can of dust swept from his porch; a laboratory analysis showed that 75 per cent of this was cement dust.

[The authors' reply to this discussion will be found on page 43.]

North-Eastern Centre, at Newcastle, 28th January, 1935.

Mr. W. S. Coates: The problem on which the authors have been occupied is to devise means of removing quantities of highly corrosive gases—sulphurous and sulphuric oxides—present in small proportions in enormous quantities of flue gases, which contain at the same time appreciable quantities of solid suspended matter of widely varying particle size. This is a problem which is bristling with difficulties, particularly in the direction of devising plant for continuous operation, but the difficulties appear to have been overcome by the application of fundamental physical and chemical principles.

One of the difficulties in work of this nature is the disposal of the material produced in the process. Sulphurous acid and its salts, the sulphites, have a strong affinity for oxygen and this property precludes their disposal by discharging them into rivers which are controlled by Conservancy Boards, who are notoriously averse to reducing the oxygen content of river waters on account of the danger to the lives of river inhabitants and of the delay in self-purification. This difficulty has been overcome by the ingenious device of using the original fill of water in continuous cycles, after removing the major portion of solid matter produced during each cycle. These salts are not very soluble, but they easily yield supersaturated solutions, which are unstable. The addition of crystals of these salts to such solutions eventually reduces the concentrations of the dissolved salts to the more stable saturated condition. This fact, and the fact that calcium sulphite is less soluble in alkaline solutions than in acid solutions, led to the happy idea of designing the delay tank and of adding the lime to the circulating liquor immediately before the delay tank. The object of this part of the cycle is, presumably, to prevent the deposition of calcium salts from supersaturated solutions on to the surfaces over which they flow. I am not quite clear as to the necessity for this precaution. The majority of those salts which are soluble in water possess positive solubility coefficients, i.e. they are more soluble in hot water than in cold water. When, therefore, hot saturated solutions of such salts are passed over cold surfaces, the salt is deposited as a scale directly on the surface. Calcium carbonate is such a salt, and this fact partly explains why carbonate scales are deposited, for example, on the water feed lines to boilers. There are certain salts, including calcium sulphate and lime, whose solubility coefficients are negative, i.e. such salts are less soluble in hot water than in cold. If, therefore, a saturated solution of calcium sulphate is passed over a surface which is at a lower temperature than the solution, it would appear to be impossible for scale to be deposited. A supersaturated solution of calcium sulphate in contact with a cooler surface would be expected to deposit calcium sulphate as a suspension in the liquor rather than as a scale on the surface. If, on the other hand, a saturated solution of calcium sulphate is passed over a surface at a higher temperature than the solution, the calcium sulphate is deposited as a scale directly on the heated surface. This explains why calcium-sulphate scales are produced

* H. Toensfeldt: *Transactions of the American Society of Mechanical Engineers*, 1927–28, vol. 49–50, "Fuels and Steam Power," p. 77.

on, for example, boiler heating surfaces. There appears to be no reason why the surfaces in the plant which are in contact with liquor saturated with calcium sulphate should be at a higher temperature than the liquor, and I should be obliged if the authors would enlighten me on this point. The use of delay tanks is not a new idea; they have been used for many years in water-softening plants. I should like to ask the authors whether they have experienced trouble due to choking of the ring main conveying the lime slurry. This trouble would appear to be easily possible.

A most interesting feature of the authors' work is the development of the pH meter. The pH value of a solution was at one time purely a mathematical conception. The hydrogen-ion concentration meter, to give it its full name, has now been used for several years as a laboratory instrument, and the authors are to be congratulated on developing a commercial instrument. A tremendous amount depends on this instrument, and I imagine that it will require a good deal of attention. Have the authors experienced trouble due to settlement of solid matter in this instrument?

The successful operation of the plant appears to require careful control, to within fairly narrow limits, of both the lime addition and the solids extraction, and I imagine that there will be many plant executives who will not view the continuous operation of the plant, in a trouble-free manner, with the same equanimity as the authors. Both the capital costs and the total running costs of a plant of this nature are high, and unfortunately, according to the authors, there can be no financial return to an industry making use of it. The only product obtained from the plant is the solid matter discharged by the filters. This consists of 60 per cent flue dust and grit, 20 per cent calcium sulphite, and 20 per cent calcium sulphate. Would it not be possible to utilize this material in the manufacture of sulphuric acid, or cement, or plaster? Bearing in mind that the main object of this plant is to benefit the community at large, it seems only reasonable to suggest that the community should pay the bill.

The plant is only capable of removing up to 70 per cent of the nitrogen oxides, and a lower proportion of dust is removed from gases which have previously passed through a wet dedusting plant than from gases which are passed directly into the plant. It would be interesting to learn the reasons for these discrepancies, and also what changes will be required in the plant in order to remove all the acid and suspended matter.

Finally, is it really desirable to remove the sulphur dioxide from the gases discharged into the atmosphere? There would appear to be no doubt that the removal of suspended solids from factory chimney gases and the prevention of tar and smoke emission from domestic chimneys is highly desirable in the interests of public health. Sulphur dioxide, however, is an extremely powerful germicide. We are all aware of the use of this gas in fumigating a room which has been occupied by a patient suffering from contagious or infectious disease. The Food and Drugs Act permits the use of limited quantities of sulphur dioxide in certain foods and preserves. It occurs to me that it would be more in the interests of public health to increase the sulphur dioxide in the atmosphere in order to combat the epidemics of air-borne diseases in densely populated areas, rather than to adopt costly methods of removing it. I am, of course, aware of the damage which sulphuric acid can do to certain building materials; CO_2 can also do a good deal of damage, but no one has suggested that we ought to remove this gas from the atmosphere, and no one has yet devised a satisfactory means of overcoming the ravages of frost.

Mr. W. Innes: The process suggested by the authors, and the method by which it has been developed, emphasize the fact that steam-raising is essentially a chemical process which has long been left entirely in the hands of engineers. It shows that the more intimate the contact between pure chemistry and engineering the more effective will be the means available for the development of this important operation.

The essential simplicity of the authors' process recommends it to us. In water-softening, delayed precipitation of soluble material by the formation of a supersaturated solution is a real difficulty; here, this very delay is used as a means of getting precipitable material out of the scrubbers to a place where it may be precipitated without interfering with the flue-gas flow.

It is unfortunate that when sulphur dioxide (SO_2) dissolves in water to form sulphurous acid (H_2SO_3), the solution has a considerable vapour pressure of sulphur dioxide. Thus it is not possible to remove SO_2 by means of water alone. It must be fixed with an alkali. In this case the alkali used is really the soluble calcium bicarbonate formed from lime by excess of CO_2, presumably through the carbonate, thus:—

$$\underset{\text{Lime}}{CaO} \xrightarrow{CO_2} \underset{\substack{\text{Insoluble}\\\text{calcium}\\\text{carbonate}}}{CaCO_3} \xrightarrow[\substack{\text{Carbonic}\\\text{acid}}]{H_2CO_3} \underset{\substack{\text{Soluble}\\\text{calcium}\\\text{bicarbonate}}}{Ca(HCO_3)_2}$$

This material forms calcium sulphite, which is in part oxidized to calcium sulphate by atmospheric oxygen:—

$$Ca(HCO_3)_2 \xrightarrow{H_2SO_3} \underset{\substack{\text{Sulphite}\\\text{(insoluble)*}}}{CaSO_3} + 2H_2O + 2CO_2$$

$$CaSO_3 + \text{atmospheric oxygen} \longrightarrow \underset{\substack{\text{sulphate}\\\text{(insoluble)*}}}{CaSO_4}$$

* Both readily form slightly supersaturated solution.

It is much easier to oxidize the sulphite to the sulphate than to oxidize SO_2 to SO_3, but both are retained in solution by supersaturation, until the liquid has left the scrubbers, or, at least, the conditions are such that deposition does not take place as an adhering scale in the packing material.

Such a process, run with excess of lime, would be liable to give a deposit of calcium carbonate, besides being wasteful; whilst with too little lime the acids in the flue gas would not be entirely captured. Hence it is essential that the lime additions should be rapidly regulated to the acid load, and the potentiometric method

of estimating the pH value of the circulating liquor is thus not only interesting but of fundamental importance in the running of the plant. Under correct running conditions all the lime is removed as insoluble material; and, provided these solids are precipitated outside the scrubbers, or at least never upon the surfaces of its elements, and furthermore are removed from the circulating sludge at an appropriate rate, then a very promising and interesting non-effluent system seems possible.

As the plant must be constructed of very special materials, and the use of dissimilar metals avoided, it would appear that the first cost would be high, and owing to the abrasive nature of the circulating medium the plant would have high maintenance costs.

In conclusion, I should like to ask the following questions. (1) What kind of wood is used in scrubbers? Does it show any tendency, through mineralization or other alteration of surface in service, to promote precipitation as scale on its surface? (2) The use of sodium carbonate for de-scaling is interesting. How does it work? (3) Do the different types of dusts obtained from different kinds of coal differ in the promotion of crystallization on their surfaces? (4) Is the system of automatic lime-addition satisfactory? (5) Is there any corrosion by wet gases after they have left the scrubber? (6) Why is the recovery of saleable by-products not encouraged? (7) If seepage from sludge penetrates into the ground, will lead-sheathed cables and ferro-concrete piles be attacked?

Mr. A. Howell: I have had the pleasure of seeing, under the guidance of one of the authors, the pilot plant at Billingham in operation. The thing that amazed me most about the plant was the concentration of solids in the re-circulating liquor, and I wondered how it was possible with such concentrations to take any further solids out of the gas or to prevent blockage in the pipes. That this was being done was fully demonstrated by the state of emission from the chimney; also the removal of SO_2 was demonstrated by the ability to sniff a sample of the gas up one's nostrils without feeling any ill effects.

With regard to the authors' remarks as to the ability to do without the solids separation plant, it would appear desirable from consideration of this aspect alone to locate future power stations erected in conjunction with the national transmission grid so that sufficient cheap land for reclamation purposes can be secured to allow of the purge being discharged to waste during the life of the power station, and so save the cost of solids separation plant and the attendant handling and disposal of solids. At present this part of the problem of flue-gas washing is not nearly so easy of solution as the authors suggest by dumping at sea, more especially in the case of an inland power station. The question of handling and disposal of the wet solids has quite a serious aspect.

If there were sufficient land for dumping purposes for a period of years I imagine that there would still be installed cyclone extractors or electro-filters of 80 to 90 per cent efficiency, so as to collect the dust in dry form and handle this to the dumping ground by means of an efficient hydraulic sluicing system similar to that in use in many power stations, leaving a clean gas to be dealt with by a scrubber. This would save a considerable amount of plant for solid separation, and would most probably result in saving in space.

Whilst admitting that the installation of cyclones or the like in addition to gas-washing plant would be more expensive, I imagine that the washing of cleaned gas by the process described would be just as easily accomplished as would the washing of an uncleaned gas, in which case the plant would be cheaper to operate as, owing to the solids being easily handled in the dry collected form, the wet-solids handling plant such as centrifuges and rotary vacuum filters, etc., would be eliminated.

The handling of wet solids is of importance, bearing in mind that from a 300 000-kW power station operating at 60 per cent load factor there would be between 80 and 100 tons of wet solids to handle per day in the case of a stoker-fired boiler plant, and approaching 150 tons per day where pulverized-fuel-fired boilers were installed. The area of land required for reclamation purposes, on which to dump the solids discharged from the flue-gas washing plant during the useful life of a 300 000-kW station, would be approximately from 50 to 60 acres.

I do not agree that the design shown in Fig. 16 is an economical proposition, as suggested by the authors, especially when regarded as a complete boiler house. It is not economical to contemplate installing stokers 50 ft. above ground level, bearing in mind the great weight of the boilers and coal-storage bunkers, also the handling of coal by conveyors to such great heights. The design shown in Fig. 14 would prove more economical, seeing that the washing plant is placed on the roof above the boilers, the heavier loads being nearer ground level.

[The authors' reply to this discussion will be found on page 43.]

NORTH MIDLAND CENTRE, AT LEEDS, 19TH FEBRUARY, 1935.

Mr. P. G. Hieatt: It appears to me that the installation of the smoke and acid removal plants at Battersea and Fulham is the thin edge of the wedge, and doubtless in the near future it will be compulsory to install similar plant at the smaller power stations. The figures given in the paper only concern stations of the size of Battersea, and I should like to know whether the capital and running costs in the case of the small stations are likely to be larger in proportion.

Mr. W. Dundas: It appears somewhat unfair that electric power stations should have been singled out for attack in the campaign against atmospheric pollution, when in reality they should receive credit for improving the condition of the atmosphere by encouraging the development and use of electricity in the home, thus cutting down the domestic coal consumption, which is chiefly responsible for the dirt-laden atmosphere in populated areas; a condition accepted by many as the sacrifice to be made for comfort and convenience.

The effect produced by the various sources of contamination shown in Fig. 1 is very striking, and illustrates the concentration produced by a large power

station. The authors admit not having any definite information on the extent to which industry affects the problem, so that the curve relating thereto in Fig. 1 is hypothetical and obviously will vary considerably in different localities, as also will the relative sequence of the three curves. This will naturally have some bearing on the necessity for gas washing. Extraordinarily high efficiencies have been obtained with existing installations, and it appears questionable whether it is necessary to go to such extremes, as one would expect a more reasonable tolerance to be allowed, especially on the score of expense. I should like the authors' opinion as to what they consider a reasonable SO_2 content at ground level.

With the tendency to improve combustion conditions in factories, it is possible that large industrial concerns may be faced with a similar problem in the future, and I am inclined to think that they would fight shy of incurring the added expenditure involved in flue-gas washing and would adopt the more expedient alternative of installing internal-combustion engines, which already are a formidable competitor to the electricity supply industry.

The authors do not approve increasing the height of chimneys, which of course can only assist in diffusion; but, judging by the present trend of events, that practice is acceptable in a large number of cases and is attractive where limitation of space prohibits the installation of gas-washing apparatus.

Reference is made in the paper to experience with coals of low sulphur content only, and it is not surprising to find that troubles have occurred on account of deposits. Experience elsewhere has proved that certain coals are particularly difficult to deal with in that respect, and I should like to have the authors' comments on that point. It would appear that by-pass flues are desirable for banked periods, and should be allowed by the authorities. I think the authors should have taken into account the costs involved in the disposal of solid matter, as that item is likely to prove expensive. The figure of 1s. 6d. per ton is by no means an extravagant one, and the summary of the total annual costs given in Table 7 should be debited with an additional sum of £5 000–£6 000 on that account.

It seems only reasonable to expect that if the electricity supply industry is given the added responsibility of improving atmospheric conditions, some consideration should be given in return by the rating authorities commensurate with the effect on the demand made by the public health department, which is usually a high percentage of the rates.

Mr. C. H. Sparks: My observations suggest that there is something unexplained and inconsistent in the extent of pollution by sulphur fumes in various localities. This inconsistency appears to be due to topography and climatic conditions, and also to the temperature at which flue gases are discharged to atmosphere. As an instance of this it may be noted that at Barton, 10 years ago, coal of comparatively low sulphur content was burned and yet the conditions of atmospheric pollution resulted in those legal proceedings which have given such impetus to the business of building high chimney stacks and the development of equipment for dust and sulphur elimination. It is well known that the temperature of the gases discharged to atmosphere at this station was extremely low, judged by the standards of that day.

In Russia two plants may be mentioned, in the first of which 4 500 tons of lignite are burned per day. The fuel contains not less than 4 per cent of sulphur and 30 per cent of ash; at the second, over 1 000 tons of coal—containing 5–8 per cent sulphur and 20 per cent ash—are burned. The stacks are 230 ft. high and the leaving gas temperatures exceed 400° F. In each case no personal inconvenience has been suffered due to the presence of sulphur gas; in fact, from this point of view the surrounding localities may be looked upon as health resorts.

In Washington, a city of beautiful parks, gardens, and buildings, the new power and heat stations have no stacks, but make use of electrostatic catchers for the removal of dust. It seems probable that in this case care may be exercised in the choice of coal, and that only those coals having a low sulphur content are accepted for burning in the city area; if such is the case we might well follow this example.

Mr. G. B. Melton: The authors tell us that if a power station be erected within 6 or 8 miles of a town it is probable that a nuisance will be caused, and that this probability becomes almost a certainty if the station is equipped with pulverized-fuel firing. This conclusion is drawn from data which are inconsistent, and is supported by calculations of rates of dissipation which can be invalidated by the vagaries of the wind. From the data set out in the paper I note that the atmospheric conditions at Rievaulx Abbey are similar to those at Watford, some 15 miles outside London; this is difficult to believe.

Whilst the authors' conclusions may be true in certain circumstances they are manifestly incorrect in others. Do they seriously suggest that the atmosphere of Sheffield would be materially improved if the power stations in that city were removed to the Isle of Man? On the other hand, one can agree that the erection of a large station within a short distance of Beverley or Harrogate would quite easily give rise to complaint.

I suggest that the economical solution of the difficulty is to build the large stations well clear of the towns, and would remind the authors that this course is quite often advantageous from considerations entirely divorced from the question of chimney emissions. As an argument against this the authors quote the costs of transmission in the London area, but I would point out that these costs are quite exceptional. Stations built in the towns should be such as are required to supply the heat requirements of the houses and factories; the output of electrical energy being regarded as a by-product and regulated in accordance with the demands for heat, the large remote stations acting as balancers and supplying the greater portion of the electrical energy.

This system would remove the dangerous "point discharge," and as it would also obviate the general combustion of coal it should be fairly effective in clearing the atmosphere. Such systems are, as is well known, in use in America, Germany, and Russia, and it cannot be claimed that a similar system is impracticable in this country.

I think it will be very difficult to convince a Yorkshire

millowner or mineowner that he should pay more for his power in order that the life of the local town hall may be extended. I fear that the authors have overlooked the hard facts that unless the prospective consumer can be shown how his personal costs will be reduced by the purchase of power he will continue to produce his own, and collectively in so doing contaminate the atmosphere to a much greater extent than do even the present power stations. Probably because his emissions are spread over a wide area the result is less obnoxious than the effect of a carefully controlled power station.

The cost of the proposed treatment is, we are asked to believe, negligible; in actual fact, the capital charges amount to 10 per cent of the whole cost of a station and the running costs to 11 per cent of the actual running costs of a typical plant. These figures are based upon the estimates contained in the paper and are additional overhead costs for which the undertaker receives no return. They are actually very substantial increases, and corresponding reductions would be considered to warrant considerable effort and expenditure of money. I cannot accept the statement that these costs would be simply handed on to the consumer; the power user will not become a consumer unless it pays him to do so. It must be borne in mind that the estimated costs are based upon the operation of a very small experimental unit which is situated in a position where the very best chemical skill is available for its control. I doubt whether such favourable results would be obtained—at least for some time—from a large installation operated as part of the equipment of a power station and subject to the exigencies of every-day usage.

If the object of the paper is to improve the general condition of the atmosphere of the country I consider that it is not really helpful. In my opinion this object will best be achieved by reducing the cost of electricity until it is universally used, so that all coal is burnt under proper conditions. Those present who recall the conditions in this area during the 1926 coal strike will, I think, be in agreement with this view.

The Authors' Reply to the Discussions at London, Newcastle, and Leeds.

Messrs. J. L. Pearson, G. Nonhebel, and **P. H. N. Ulander** (*in reply*): The matters and questions raised in the discussion can be most conveniently treated in sections as follows:—

I. SO_2 pollution and general.
II. Comparison with the Battersea system.
III. Technical details of the Howden-I.C.I. system.
IV. Disposal of mud.
V. Economics.

(I). SO_2 Pollution and General.*

(A) *Historical.*

The Barton case was incidental in the history of government and public interest; it did not originate such interest. Thus:—

(*a*) In 1905, at the Coal Smoke Abatement Conference, Dr. Rideal calculated that London was then passing annually into the air between one-half and one million tons of acid;

(*b*) In 1908, Cohen and Ruston were carrying out at Leeds some of the work described in their book "Smoke" (second edition published 1925);

(*c*) In 1918, there appeared the first of the annual reports of the D.S.I.R. on atmospheric pollution;

(*d*) In 1924, and again in 1926, Sir Frank Baines (then Director of H.M. Office of Works) investigated complaints at Regent's Park, and in the latter year submitted officially a proposal that power stations should be definitely required to wash sulphur out of flue gases;

(*e*) In 1926, a précis of the main report by Sir Frank Baines on the fabric of the Houses of Parliament was presented to Parliament;

(*f*) In 1927, the first third of the Battersea power station was sanctioned on condition that sulphur removal was incorporated.

(Note:—The Barton case was first "tried" in July, 1928.)

* In reply to Dr. Pearce, Lt.-Col. Edgcumbe, and Messrs. Coates, Dundas, Melton, Selvey, and Sparks.

(B) *The Origin of the Interest in SO_2 Emission.*

Government and public interest in SO_2 emission has grown with the increase in coal consumptions of individual power stations and with the raising of the general level of social service and welfare, both of which have been considerable since the war. The interest is natural and, in the circumstances, inevitable. There are to-day a number of power stations in Great Britain, each putting into the atmosphere daily more acid than the daily make of the average of the larger British sulphuric acid works.

In atmospheric pollution the most important aspect is the mass rate of emission of the pollution from a single source, and, for this purpose, all the chimneys of a power station must be regarded as constituting a single source of emission. The effects arising from the burning of, say, 2 000 tons of coal per day by a large number of small sources of emission spread over a relatively large area, however objectionable they may be, are practically negligible compared with those arising from the consumption of coal at a similar total rate at one source.

There are no authoritative data defining precisely the dividing line between harmful and harmless concentrations of SO_2 at ground-level. As some sort of a rough guide it can be accepted that a concentration of 1 part per million by volume over long periods is both unpleasant and harmful. Ground concentrations under normal weather conditions, however, constitute but one of the six phases of the "effect mechanism" of SO_2 pollution.

SO_2 may or may not be an excellent germicide if it were to remain as SO_2 in very low and controlled concentrations in the atmosphere. Actually it is rapidly oxidized by atmospheric oxygen in sunlight or after being dissolved in water. The oxidized solution is sulphuric acid and this attacks the respiratory organs, affects the heart, and damages buildings.

(C) *Extraction Efficiencies.*

With the superimposition of large emission from single sources upon the normal widely-spread domestic and

industrial emission in urban areas, very high extraction efficiencies are to be demanded justifiably for the large sources of emission as explained in Section I of the paper. Moreover, the greater the coal consumption of the individual source (other matters being equal) the higher must be the efficiency of extraction required. A source burning 2 000 tons of coal per day should have a higher efficiency of extraction than one burning 1 000 tons of coal per day; thus 98 per cent extraction for the dust and sulphur of the former will give the same mass rate of emission of pollution as 96 per cent extraction for the latter.

In deciding upon the efficiency of extraction, apart from the rate at which coal is burnt, there is logically only one other matter to be considered, viz. the wealth in buildings and human beings congregated in the field of attack of any particular source of emission. The greater such wealth in this field the higher should be the efficiency of extraction.

For large urban areas the logical basis for extraction efficiency should be that required in any particular case to give an authorized amount of pollution, *the real standard being a permitted mass rate of emission for a single source*, as laid down by public authority for the urban area concerned. It should be noted that 95 per cent extraction will allow 5 times the mass rate of pollution of 99 per cent extraction with the same rate of coal firing, and that 95 per cent extraction will allow a mass rate of pollution equal to that of 99 per cent extraction from 5 times the rate of coal burning.

(D) *Measurement of Acid (SO_2) Atmospheric Pollution.*

The suggestion of using polished metal plates is an interesting one, but it would appear that the relative humidity of the air at the time of the test would very considerably affect the results so obtained. We favour the lead-peroxide candle method developed by the Building Research Station (see their Annual Reports for 1931 and 1932) and suggest that Lt.-Col. Edgcumbe try the two methods out, side by side, over an extended period of time.

The figures given for SO_2 pollution at Rievaulx and at Garston (Watford) have been misinterpreted. In both places the free SO_2 at ground-level is of the same order, but the amount of SO_3 deposited with the rainfall at Garston is extremely high and approximately equal to that at Westminster, illustrating the drift of SO_2 over London. At Rievaulx Abbey the stonework is *now* showing serious sulphate attack due to drift of SO_2 from the West Riding industrial district. The effects at both places are consistent with the distribution of atmospheric pollution as dealt with in the paper.

The details of the Russian plants, as mentioned in the discussion, cannot be interpreted or explained without further information concerning atmospheric and ground conditions in the locality referred to, and concerning the composition of the flue gases, etc.

(II). Comparison with the Battersea System.*

(A) *Comparison in Size of Scrubbers.*

It is true that the cross-sectional area of, and the area of absorbing surface in, the grid-packed scrubber are about equal to those pertaining to *the uptake tower* at Battersea. Since, however, the Battersea system includes a "downcomer" of dimensions nearly equal to those of the uptake tower, a horizontal flue of generous proportions, in which some scrubbing occurs, and grit arrestors, the real comparison in size between the two scrubbers, as described, is better represented by stating that the grid-packed scrubber:—

(*a*) Effects in some 20 ft. of height and with a 3 ft. 6 in. depth of packing what Battersea does in a "height equivalent" of about 350 ft.

(*b*) Could be located and with space to spare in the horizontal flue at Battersea. The grit arrestors would then be rendered unnecessary, their removal providing far more than ample space for flues to lead away the gases from the grid scrubbers.

(*c*) Is actually in volume about 1/10th of the volume used at Battersea.

(B) *Comparison of the Basic Methods of Scrubbing.*

The above comparison in size is between the Howden-I.C.I. plant as operated as a non-effluent system and the Battersea plant as actually installed. Both plants depend upon the addition of an approximately equal amount of alkali to fix and remove the SO_2 and SO_3 from the flue gases. In the Howden-I.C.I. system, *as a non-effluent* system, practically all the alkali required is added to the scrubber as *purchased* lime or chalk. It was clearly intimated in the paper, however (Section III H), that the system could be modified to take advantage of *any* favourable conditions—as regards effluent and, therefore, as regards the use of unpurchased alkali—which might pertain to any fortunately situated power station. This can be done even to the extent of using no purchased alkali at all.

In the Battersea installation, of the total alkali required there is added:—

(i) 20 per cent or less as purchased CaO, put in at the top of the tower uptake;

(ii) 80 per cent or more as CaO obtained without payment, i.e. obtained gratuitously in the form of calcium bicarbonate alkalinity from the River Thames—for 80 per cent or more of the absorbed SO_2 and SO_3 is neutralized by adding the scrubber-acid-effluent to the return condenser water.

At Battersea, the burning of 1 000 tons per day of coal containing 1 per cent sulphur destroys, by neutralization of the scrubber effluent, the total alkalinity of 25×10^6 gallons per day of Thames water, the average alkalinity of which is approximately 20 parts $CaCO_3$ per 100 000.

Battersea at present not only obtains most of its alkali without payment, but also obtains free transport for the salts resulting from the absorption and fixation of the SO_2 and SO_3 of the flue gases, these salts being carried away to the sea, as calcium sulphate in solution, by the River Thames.

As stated above, the Howden-I.C.I. non-effluent system can be changed to an effluent system in order to take the fullest possible advantage of any favourable circumstances, appertaining to "free" alkali and free transport for calcium salts, such as exist at Battersea. The importance of the non-effluent system was stressed in the paper because there appears to be little likelihood

* In reply to Dr. Pearce and Mr. Erith.

of the further extension of effluent systems being permitted on the Thames or similar rivers. This view is strongly supported in the recent White Paper on the gas-washing plant for the new Fulham power station (see Cmd. 4885—1935).

(C) *The Practical Restrictions on the Further Use of Effluent Systems.*

The Metropolitan Water Board is not allowed normally to reduce the flow of fresh water over Teddington Weir to below 170×10^6 gallons per day, but from July to December, 1934, sanction was obtained for a reduction of flow down to 50×10^6 gallons per day, an amount capable of providing sufficient alkali for Battersea to burn 2 000 tons per day of coal containing 1 per cent sulphur.

Thus the Thames, in a dry summer, can provide sufficient "free" alkali for the Battersea station only. In a normal summer it could provide as free alkali only a small fraction of the total alkali requirements for the London power stations. This clearly raises such piquant questions as: "Is there to be a free scramble for such small amount of gratuitous alkali as there is going in the river, the power station higher up the river always winning?" or "Is the concession to Battersea to be denied to other stations and in particular to municipal power stations?"

A short time ago we put forward for a certain London power station a proposal for an effluent system, which would meet requirements laid down by the Port of London Authority, which would not take so much alkali from the river as Battersea, and which would not entail so much sulphate being carried away by the river. That proposal was not accepted. The fact still remains, however, that the Howden-I.C.I. system, as an effluent system, is available for any power station situated higher up the river than Battersea.

Even if the Thames authorities had sufficient alkali to give away free—in order to permit a wide extension of effluent scrubbing—there would be grave objections, especially on behalf of down-river users, against turning the water of the Thames into a saturated stream of calcium sulphate in solution. Moreover, the amount of calcium sulphate that can be carried in saturated solution by the river is limited, and this would in any case provide a restriction on the wide adoption of effluent scrubbing.

(D) *Comparison of Costs* (*Capital and Annual Costs*).

A strict comparison in costs would mean re-estimating the Howden-I.C.I. system on the basis of

(*a*) an equal amount of free alkali;
(*b*) an equal amount of free transport for the calcium sulphate
} as in the Battersea system,

for the Howden-I.C.I. system is capable of modification from 100 per cent free alkali to 100 per cent purchased alkali, i.e. from a straight-through cycle to a completely closed cycle.

There are, as explained in the paper, three main sections of plant:—

(i) The scrubbing section (this constitutes the main part of the plant in any system),

(ii) The lime-mixing section (the size of which depends upon the ratio of purchased to free lime),

(iii) The solids-separation and mud-disposal section (which depends upon the extent to which free transport by the river is available for the calcium salts).

As far as a comparison on an equivalent basis with the Battersea installation is concerned, in capital costs:—

(*a*) The Howden-I.C.I. plant will always be the cheaper, owing to its relatively small size.

(*b*) There can be little difference in the lime-mixing and solids-separation sections, since these may be regarded as using more or less standard or well-known types of apparatus.

Similarly, as far as a comparison of the total annual charges is concerned:—

(*a*) The Howden-I.C.I. plant will have the advantage in charges arising from a percentage on capital.

(*b*) There can be little difference in lime costs and miscellaneous operating charges (the overall power costs for pumps and fans in the non-effluent system are the same as those for Battersea). Referring to Table 7 of the paper, the running charges for the Howden-I.C.I. non-effluent central system, with 1·5 per cent sulphur coal, are:—

(*a*) 0·0053d. per kWh for lime, and

(*b*) 0·0034d. per kWh for power, labour, and maintenance.

If 85 per cent of the lime were supplied free of charge, as at Battersea, the running charges would be 0·0042d. per kWh, i.e. lower than the running cost of 0·005d. per kWh quoted for the Battersea central system with 1 per cent sulphur coal.

(E) *Capital Costs as Given in the Paper.*

In Table 5 the figures given cover foundations, structural steelwork, and such flues as are additional to those required if no flue-gas cleaning plant were installed. The figures, however, do not refer to any particular power station. Local conditions will naturally have an appreciable influence on the lay-out and hence on the capital cost of any specific installation.

Running costs will be similarly affected by local conditions, e.g. by the sulphur content of the coal burnt and by the price of alkali.

(III). Technical Details of the Howden-I.C.I. System.*

(A) *The Size of the Pilot Plant.*

The stepping-up in the scale of operations from a pilot plant to a commercial plant is a common criticism of all new processes and systems. Some teething difficulties are usually encountered in the first commercial venture, but this oft-repeated criticism has had little effect upon industrial progress. We have access to considerable experience in this respect.

In the present case it should be noted that full-scale plants consist of a number of cells each of the size of the pilot plant. The difficulties to be expected in increase of plant size are in even gas and liquor distribution. These can be overcome by correct design, and account

* In reply to Dr. Pearce, and Messrs. Coates, Erith, Fielding, Innes, and Selvey.

has been taken of this matter. Apart from the scrubbers, the remainder of the plant consists of tanks, pumps, valves, pipe lines, and other well-tried apparatus.

(B) *Operation of the Pilot Plant.*

Operation with the non-effluent system described in the paper is about as simple as any form of operation can possibly be, for it is reduced to:—

(*a*) The reading of, or automatic control by, a pH recorder.

(*b*) The reading of a continuous density indicator and the corresponding manual or automatic control of the rate of purge to the filters.

There is no close control of liquor and gas rates, and there are no complex liquor and gas analyses with their attendant delays and lags in plant control. It was these delays and lags which rendered progress somewhat slow during the investigations on the pilot plant, before the pH recorder was fully developed.

Suggested difficulties with regard to the small range of pH are non-existent, since the solution is buffered with respect to pH by the relatively high concentration of suspended $CaCO_3$ and $CaSO_3$. The delay tank itself also contains sufficient liquor to smooth out and to prevent rapid fluctuations in pH. No trouble was experienced on the pilot plant from such hypothetical difficulties.

Some misapprehension has occurred concerning the mal-operation referred to in the paper, and the provision of cleaning facilities. The term " mal-operation " was intended to cover matters such as the operatives losing the washing liquor or the solids in suspension, from inadvertence in the handling of control valves, i.e. accidental matters which, while being largely preventable, do happen occasionally, if infrequently, with all types of plant. It is good practice to make some provision limiting the consequential results of such accidents.

(C) *Some Details of the Plant and Process.*

Calcium sulphate is not readily precipitated, and consequently supersaturated solutions are rapidly formed within the scrubber unless time is allowed for crystallization of the liquor before each re-circulation. The temperature argument put forward by Mr. Coates does not hold in any case for the scrubber, since the maximum solubility of calcium sulphate occurs at the operating temperature (120° F.) of the scrubber liquor.

No troubles due to scale or settlement have been experienced in either the lime slurry supply main or the pH recorder sampling cell. The design of the latter is such that a constant stream of liquor is withdrawn from the cone of the vessel as well as from the overflow (see Fig. 8).

The wood used in the scrubber was common red deal. Other woods have been tried with equally satisfactory results. No mineralization of the wood has occurred after over 2 000 hours' service. No special materials have been used in the construction of the plant, other than staybrite pump impellors and rubber-lined pipe bends and pump casings. The corrosion of a mild-steel exit flue after the scrubber by the wet CO_2-laden gases has been negligible. Painting of this flue by heavy bitumastic paint is, however, recommended.

Corrosion of lead-covered cables will not occur if the plant liquor and sludge penetrate into the ground, and well-cast compact concrete also will not be attacked.

Sodium carbonate is an effective cleaning agent because it reacts with the calcium sulphate and sulphite, forming calcium carbonate, which is in turn slowly dissolved by the dissolved carbon dioxide in the scrubber circulating liquor.

(D) *Extraction Efficiencies.*

Oxides of nitrogen are notoriously difficult to remove by scrubbing. They are present mostly as NO, which requires to be oxidized to NO_2 before solution can take place, and such oxidation is a slow process. The scrubber packing has been designed for efficient SO_2 absorption. A different form or amount of packing is required for efficient oxidation of NO and absorption of NO_2.

As regards dust-removal efficiencies, it is obvious that it is more difficult to obtain a high percentage removal from a gas which has already been partially dedusted and contains only the smaller particles at a reduced concentration. Actually the exit test from the scrubber is practically the same with both un-dedusted and partially dedusted gas from a powdered-fuel boiler—as is to be expected. Removal efficiencies, in any apparatus, depend upon the concentration and grading of the dust presented to the apparatus. In practice it is only the end conditions that matter.

(E) *Soot Removal, etc.*

The apparatus has not been tested for the removal of black smoke from a hand-fired furnace. It should be noted, however, that:—

(*a*) In the tests with black smoke mentioned in the paper, where the particles are extremely small, the appearance of the chimney indicated very high extraction efficiencies for the " sublimed " carbon or sooty particles.

(*b*) An oily scum always collected on the settler of the pilot plant whenever combustion conditions in the associated boiler were poor, again indicating that the removal of sooty particles was taking place.

In determining the efficiency of dust removal on the pilot plant, tests were made with a sampling nozzle designed by the late Professor Gibbs (Brit. Pat. 416516). The results thus obtained were in close agreement with those resulting from tests with other apparatus.

(IV). Disposal of Mud.*

Some misapprehension is evident concerning the difference in the amount of sludge between pulverized-fuel firing and stoker firing. In the example given in Section V of the paper, the flow sheet being based on pulverized-fuel firing, the weight of " wet " sludge for disposal, for a power station of 120 000 kW installed capacity, is between 21 and 22 tons per hour. Of this, some 60 per cent (or 13 tons per hour) is wet ash and dust from the coal. This amount, or its equivalent on a dry basis, would require removal and disposal in any case and whatever system of flue-gas cleaning was installed. The additional 8 to 9 tons of calcium salts, with non-effluent cleaning, is unlikely therefore to impose any such

* In reply to Dr. Pearce and Messrs. Coates, Dundas, Erith, and Innes.

great difficulties or expense as has been suggested by various contributors.

With stoker firing, without any scrubbing system, there would be, say, 8 to 9 tons per hour of dry ash. The non-effluent scrubbing system would mean a further 7 to 8 tons per hour of *wet* calcium salts (with a small admixture of flue dust) for disposal. Thus, with any system of firing, the use of the non-effluent system as described in the paper does not quite double the amount of refuse from the station, when using a 1·5 per cent sulphur coal.*

Admittedly dry ashes, in some cases, can be sold, but the monetary value involved is relatively inappreciable, and has no practical effect on the cost of power. When a uniform sludge becomes available regularly and in quantity, some useful purpose may be found for it. Clearly, however, it is desirable to maintain some sense of proportion in considering this matter.

There are no really representative figures with regard to the cost of sludge disposal. The cost depends upon:—

(i) The type of firing adopted;
(ii) Whether and to what extent free transport, by the river, of the calcium salts in solution is available;
(iii) The locality and local conditions.

For one station in which the Howden-I.C.I. system is being installed, the cost of mud disposal is nil.

No trouble is being encountered in connection with two other stations. Why should there be when at least half as much "refuse" material is exported from power stations already?

We do not discourage attempts at the recovery of saleable by-products. We have investigated various possibilities in this connection—so far without any promising results, owing mainly to the relatively small scale of the plant involved. This does not mean, however, that some economic scheme of by-product recovery will not be ultimately developed and adopted. In practice, waste products are usually available in quantity long before any profitable method of working them up into saleable materials becomes available.

(V). Economics.†

(A) *The National Aspect.*

In considering the matter from the economic side, there are two main aspects to be taken into account, viz.:—

(i) That affecting the interests of the community at large.
(ii) That affecting the interests of the particular source of emission.

The financial loss to the community through not effectively cleaning all flue-gas emissions has been variously estimated from time to time, and most of the estimates agree in giving, as a reasonably modest calculation, £40 million per annum for the direct material damage, i.e. as the evaluation of the annual cost in damage to buildings, fabrics, metal work, etc., and in additional cleaning and renovations.

To this has to be added the indirect losses arising from the detrimental effects upon the health and stamina of the urban population. For a large town it can be taken as a rough guide that within the town the inhabitants get only 70 per cent of the sunshine they should do and that this part is only 70 per cent as rich in ultra-violet rays as it should be. In these days of common sense in health, with the value now placed on fresh air and sunshine, this is a serious matter and has been dealt with by various medical authorities on many occasions, especially as regards its incidence upon both the prevalence of pulmonary and cardiac diseases and also the increased death rate during temperature-inversion conditions. It is a matter that is exceedingly difficult to evaluate in terms of money. If we assume a sum equal to that mentioned for the direct damage, we shall certainly have an underestimated figure.

On this assumption the cost to urban dwellers of not properly cleaning domestic and industrial emissions is not less than £80 million per annum, i.e. 10s. per ton of coal burnt in urban areas. That is a cost now being paid. In considering this matter it should also be remembered that modern systems of economics regard, without exception, the well-being and welfare of the great mass of the people within the country as the immediate aims and ends of all such systems.

(B) *The Economic Aspect of the Source of Emission.*

With large sources of emission, either:—

(i) They can adopt complete flue-gas cleaning and remain in the urban area, or
(ii) They can go outside the urban area and adopt some smaller degree of flue-gas cleaning (for some years to come at least).

For some power stations in large towns, to be removed or to be built well away from the centre of their loads is more expensive than to install complete flue-gas cleaning. Thus for the new final Battersea and Fulham stations the extra capital expenditure involved, if complete flue-gas cleaning had not been adopted, would have been $2\frac{1}{2}$ and $2\frac{1}{4}$ million pounds respectively, with annual charges of around £200 000 in both cases. For these and similar new stations it is much more economic both from the national and power-station interests to adopt complete flue-gas cleaning and to remain within the town. For existing urban power stations it is even more economic to remain within the urban area.

For the non-effluent process and plant described in the paper, owing to further developments since the manuscript was prepared the capital costs for a reasonably large station have been reduced to about £1·25 and £1·0 per kW of installed capacity for the unit and central systems respectively, i.e. say around 5 to 6 per cent of the capital costs of the power station as against about 40 per cent in the cases of Battersea and Fulham if complete flue-gas cleaning had not been adopted.

Running costs were shown in Table 6 of the paper, while the complete annual charges were given in Table 7. Capital charges constitute approximately one-third, lime charges one-third, and miscellaneous charges the remaining third of the complete annual charges, which are between 0·0130d. and 0·0145d. per unit generated, i.e. say about 5 to 6 per cent of the cost per unit generated, as against 12 to 15 per cent if stations such as Battersea and

* The increase is correspondingly less when a lower-sulphur coal is used, as is present practice in some of the London power stations, including Battersea.
† In reply to Mr. Selvey and Mr. Erith.

Fulham were built outside the urban area, 20 miles from their present sites. In any case, the cost of complete flue-gas cleaning is negligible on the price paid for distributed power.

Moreover, in these costs no account has been taken of the facts that some form of partial flue-gas cleaning must be installed in the alternatives and that actually only the additional costs should be considered.

Experience and logic combine to confirm that, humanly speaking:—

(i) The increase in electricity consumption so evident in the past decade will continue.

(ii) Power stations should become larger and larger in order to ensure more efficient generation with large units (already in Germany there are power stations with 450 000 kW installed capacity).

(iii) The increase in electricity consumption will, to all intents and purposes, occur in the areas with large populations (e.g. London, Lancashire, the Midlands, etc.), and that economically, both from the national interests and from the power station interests, the power stations should be located in these same areas with large populations.

Clearly, therefore, since complete flue-gas cleaning permits (*a*) economic location of the stations in the urban areas (compare the cost alternatives for Battersea and Fulham given above), and (*b*) economic generation of power in large stations, it is an economy and not an expense to the power-station management, even if the national aspect as treated under (A) above is disregarded altogether.

Apart from the gains in economic generation and location thus rendered capable of easy achievement through complete flue-gas cleaning, new or modernized stations can generate with lower costs due to:—

(*a*) The adoption of higher steam temperatures and pressures, the present general level in this country being too low.

(*b*) Obtaining powers to supply low-pressure steam to surrounding factories, as is now the practice in many U.S.A. and European towns.

(*c*) Giving greater inducements to factories to work continuously on shift. (Incidentally such factories would benefit by more continuous employment of their capital, the surrounding population by higher spending power, and the station by a more uniform rate of coal consumption and a lower instantaneous maximum rate of mass emission.)

Lastly, whatever the argument may be, the consumer will actually or virtually pay any immediate apparent costs for complete flue-gas cleaning and will garner the greater economies.

THE ALTERNATING-CURRENT RESISTANCE OF PARALLEL CONDUCTORS OF CIRCULAR CROSS-SECTION.*

By A. H. M. Arnold, D.Eng., Associate Member.

[From the National Physical Laboratory.]

(*Paper first received* 10*th November, and in final form* 20*th December*, 1934.)

Summary.

The limitations of existing formulæ for calculating the alternating-current resistance of a "go and return" system of two parallel conductors of circular cross-section are outlined, and an improved formula is developed. A table is given so that the alternating-current resistance may be evaluated in any given case in a few minutes. Experimental work was carried out to check the formula, and agreement was obtained to within 1 per cent.

Contents.

List of Symbols.

R = Direct-current resistance of each conductor in ohms per centimetre length.
R' = Alternating-current resistance of each conductor in ohms per centimetre length.
$\omega = 2\pi f$, where f is the frequency in cycles per sec.
$$x = 2\left(\frac{\omega}{R \times 10^9}\right)^{\frac{1}{2}}$$
α = (Diameter of each conductor)/(Spacing between axes of conductors).
$\beta = 1 - \alpha$.
n = An integral number having consecutive values from 0 or 1 to ∞.
m = An integral number similar to n.
$j = \sqrt{(-1)}$.
$J_n[x\sqrt{(-j)}]$ = Bessel function of the first kind, of order n, and with the argument $x\sqrt{(-j)}$.
$$\chi_n = \phi_n - j\psi_n = \frac{J_{n+1}[x\sqrt{(-j)}]}{J_{n-1}[x\sqrt{(-j)}]}$$

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List of Symbols—*continued*.

k_n is a function of α and χ_n, and is defined in the paper.
$|k_n|$ = Modulus of k_n.
$F(x)$, $G(x)$, $A(x)$, $B(x)$, $C(x)$, $f_n(x)$, and $g_n(x)$, are functions of x and are defined in the paper.
C = Correction factor.
C_∞ = Correction factor when $x = \infty$.

(1) Introduction.

The theoretical determination of the effective resistance to alternating currents of a system of two straight parallel conductors of circular cross-section forming the "go and return" conductors of a single-phase system is a problem of considerable mathematical complexity.

Several authors have put forward solutions, but their results have not been easily comparable on account of the widely differing forms in which these solutions appeared, while few of the authors have attempted to compare results given by their formulæ with experimentally determined values. In many cases the numerical evaluation of these solutions is a difficult and lengthy task which few engineers would care to undertake.

The present author has made a detailed examination of the solutions put forward by G. Mie,† J. W. Nicholson,‡ H. L. Curtis,§ J. R. Carson,‖ S. Butterworth,¶ H. B. Dwight,** C. Snow,†† and M. J. O. Strutt.‡‡ Nicholson's solution is very difficult to evaluate, and his formula is generally discredited. He made no attempt to check his formula with experimental results, and Curtis§§ pointed out in 1920 that his formula gave results which were incorrect as regards both magnitude and sign. The other authors all assume that the effect of the dielectric current may be neglected, and thereby simplify the problem enormously. This assumption appears to be justified even up to very high frequencies. On this basis, all the authors are agreed that the ratio of the alternating-current resistance to the direct-current resistance (R'/R) of two parallel conductors of circular cross-section is a function of two independent variables only. The first variable is denoted by the symbol x in this paper and is defined to be equal to twice the square root of the ratio of the circular frequency (2π times the frequency in cycles per sec.) to the resistance of the conductor in C.G.S. units per centimetre length. At a frequency of 50 cycles per sec., the value of x for a copper conductor of 1 sq. in. cross-section is approximately 2,

† See Bibliography, (1). ‡ *Ibid.*, (2). § *Ibid.*, (3).
‖ *Ibid.*, (4). ¶ *Ibid.*, (5). ** *Ibid.*, (6).
†† *Ibid.*, (7). ‡‡ *Ibid.*, (8). §§ *Ibid.*, (3).

and at any given frequency x is proportional to the diameter of the conductor. Alternatively, for a given conductor cross-section, x is proportional to the square root of the frequency. The range of the independent variable x is from 0 to ∞. The second independent variable is denoted by a in this paper, and is defined to be the ratio of the diameter of the conductor to the spacing between the axes of the two conductors. The range of the independent variable a is from 0 to 1.

Experimental values of the alternating-current resistance of parallel conductors have been obtained by A. E. Kennelly, F. A. Laws and P. H. Pierce;* H. L. Curtis;† and by the present author. There is thus ample material available for checking the formulæ put forward by various authors.

Mie's formula is simple to evaluate but is only valid for values of x less than 1. This range is so small that his formula cannot be considered to have much practial value.

Curtis's formula is much more difficult to evaluate, but is valid over a range of x up to about 4. It therefore has considerable value. Curtis showed that his formula gave results in close agreement with experimental results.

Carson‡ and Butterworth§ both tackled the problem at about the same time, and both succeeded in establishing fundamental equations for the ratio of the alternating-current resistance to the direct-current resistance (R'/R) which were theoretically sound. In order to solve these equations, however, they were compelled to introduce approximations which limited the validity of their final formulæ.

Carson solved his fundamental equations rigidly for the case of $x = \infty$, and then obtained an approximate solution for finite values of x which tended asymptotically to the correct solution as x tended to infinity. For values of a less than $0 \cdot 5$ his solution was sufficiently correct for all values of x, but when a lay between $0 \cdot 5$ and $1 \cdot 0$ his formula was liable to give results which were seriously in error for moderate values of x.‖

Butterworth, on the other hand, obtained an approximate solution which gave values of R'/R which were less than 1 per cent in error for any value of x provided that a was less than $0 \cdot 7$. For the limited range of x from 0 to $4 \cdot 7$, the error was less than 1 per cent for values of a up to unity. His formula contained functions of x which were rather difficult to evaluate. He gave a few values of these functions, but the values were too widely spaced to allow of interpolation.

Dwight's formula is exceedingly difficult to evaluate, and is therefore not further considered.

Snow's and Strutt's formulæ have the virtue of extreme simplicity but are liable to be seriously in error. They will be referred to again later.

Thus Butterworth's formula is the only one having a reasonable range of validity. The present author has therefore investigated it in great detail and has developed an improved formula having a greater range of validity.

* See Bibliography, (9). † *Ibid.*, (3). ‡ *Ibid.*, (4a). § *Ibid.*, (5a).

‖ *Example.* $x = 4$, $a = 0 \cdot 9$:—

$$R'/R = 2 \cdot 68 \text{ by Carson's formula,}$$
$$R'/R = 2 \cdot 44 \text{ by more rigid formula.}$$

The error in Carson's formula is thus 10 per cent. As the proximity effect only contributes 31 per cent to the value of R'/R, the error in the estimation of the proximity effect by Carson's formula is 32 per cent. As a increases from $0 \cdot 9$ to unity the error in Carson's formula increases at a rapid rate.

Adequate tables have been prepared so that the work of evaluating R'/R in any given case is a matter of a few minutes only.

The development of this improved formula is given in the next section. The formula is shown to give values of R'/R which are less than 1 per cent in error for any value of x up to ∞ provided a is less than $0 \cdot 92$. If x is less than 10, the formula is less than 1 per cent in error for values of a up to unity. A method of obtaining approximate values of R'/R in the small range of x and a not covered by this formula is indicated in Appendix 1.

(2) Theory.

The theoretical development given in Butterworth's paper is followed as far as his equation (18),* which is reproduced here in the slightly different form:—

$$\frac{R'}{R} = 1 + x^2\left[\frac{\psi_2}{8} + \sum_1^\infty |k_n|^2 \frac{\psi_n}{2n}\right] \quad . \quad . \quad (1)$$

Equation (1) is a rigid equation derived from the initial conditions, and it is in the approximations introduced at a later stage by Butterworth, in deriving his final formula, that the errors are to be found.

The conditions determining the values of k_n are given by Butterworth in his equation (39),† which is given here as a series of n simultaneous equations for the coefficients k_1 to k_n:—

$$k_1 = \frac{1}{2}a - \sum_{m=1}^{m=\infty} k_m \chi_m \left(\frac{1}{2}a\right)^{m+1} \quad . \quad . \quad . \quad . \quad . \quad (2a)$$

$$k_2 = \left(\frac{1}{2}a\right)^2 - \sum_{m=1}^{m=\infty} k_m \chi_m \left(\frac{1}{2}a\right)^{m+2} (m+1) \quad . \quad . \quad (2b)$$

$$k_n = \left(\frac{1}{2}a\right)^n - \sum_{m=1}^{m=\infty} k_m \chi_m \left(\frac{1}{2}a\right)^{m+n} (m+1)(m+2)\ldots (m+n-1)/(n-1)! \quad . \quad (2n)$$

The coefficients k_1 to k_n are progressively less important in determining the values of R'/R as n increases, and it is proposed in this paper to solve equation (2) only as far as k_6.

Writing out equation (2) in full, we have

$$k_1 = \frac{1}{2}a\left(1 - \frac{1}{2}ak_1\chi_1 - \frac{1}{4}a^2k_2\chi_2 - \frac{1}{8}a^3k_3\chi_3 - \frac{1}{16}a^4k_4\chi_4 - \frac{1}{32}a^5k_5\chi_5 - \ldots\right) \quad . \quad (3a)$$

* Butterworth's equation (18) is:—

$$W = \frac{1}{4}\omega\left[(K_0^2)\left\{\frac{2}{z^2} + \frac{1}{4}\psi_2(z)\right\} + \sum_1^\infty (K_n)^2 a^{2n}\psi_n(z)/n\right]$$

in which
$W =$ Energy loss in conductor $= \frac{1}{2}R'I^2$.
$\frac{1}{2}K_0 = I =$ Maximum value of current in conductor.
$z = x$ in this paper.
$K_n a^n/(2I) = k_n$ in this paper.

ω, ψ_2, ψ_n, and n have the same meanings as in this paper.

† Butterworth's equation (39) is:—

$$\sum_1^\infty K_n r^{n-1} = \frac{K_0'}{r'} - \sum_1 \chi_n K_n' \frac{a^{2n}}{(r')^{n+1}}$$

in which $K_n' = K_n$, $K_0' = K_0$. r is the distance from the axis of one conductor to an arbitrary point lying on the line between the axes of the two conductors. r' is the distance from the axis of the other conductor to the same point. $a =$ radius of conductor. χ_n has the same meaning as in this paper.

$$k_2 = \frac{1}{4}\alpha^2\Big(1 - \alpha k_1 X_1 - \frac{3}{4}\alpha^2 k_2 X_2 - \frac{1}{2}\alpha^3 k_3 X_3 - \frac{5}{16}\alpha^4 k_4 X_4 - \ldots\Big) \quad (3b)$$

$$k_3 = \frac{1}{8}\alpha^3\Big(1 - \frac{3}{2}\alpha k_1 X_1 - \frac{3}{2}\alpha^2 k_2 X_2 - \frac{5}{4}\alpha^3 k_3 X_3 - \ldots\Big) \quad (3c)$$

$$k_4 = \frac{1}{16}\alpha^4\Big(1 - 2\alpha k_1 X_1 - \frac{5}{2}\alpha^2 k_2 X_2 - \ldots\Big) \quad (3d)$$

$$k_5 = \frac{1}{32}\alpha^5\Big(1 - \frac{5}{2}\alpha k_1 X_1 - \ldots\Big) \quad (3e)$$

$$k_6 = \frac{1}{64}\alpha^6(1 - \ldots) \quad (3f)$$

Solving (3) by successive approximations,

$$\begin{aligned} k_1 = \frac{1}{2}\alpha\Big[&1 - \frac{1}{4}\alpha^2 X_1 + \frac{1}{16}\alpha^4(X_1^2 - X_2) + \frac{1}{64}\alpha^6(3X_1X_2 \\ &- X_1^3 - X_3) + \frac{1}{256}\alpha^8(X_1^4 + 4X_1X_3 - 5X_1^2X_2 \\ &+ 3X_2^2 - X_4) + \frac{1}{1024}\alpha^{10}(7X_1^3X_2 - 7X_1^2X_3 - X_1^5 \\ &- 11X_1X_2^2 + 5X_1X_4 + 10X_3X_2 - X_5) + \ldots\Big] \quad (4a)\end{aligned}$$

$$\begin{aligned} k_2 = \frac{1}{4}\alpha^2\Big[&1 - \frac{1}{2}\alpha^2 X_1 + \frac{1}{16}\alpha^4(2X_1^2 - 3X_2) + \frac{1}{32}\alpha^6(4X_1X_2 \\ &- X_1^3 - 2X_3) + \frac{1}{256}\alpha^8(14X_1X_3 - 12X_1^2X_2 + 2X_1^4 \\ &+ 9X_2^2 - 5X_4) + \ldots\Big] \quad (4b)\end{aligned}$$

$$\begin{aligned} k_3 = \frac{1}{8}\alpha^3\Big[&1 - \frac{3}{4}\alpha^2 + \frac{3}{16}\alpha^4(X_1^2 - 2X_2) \\ &+ \frac{1}{64}\alpha^6(15X_1X_2 - 3X_1^3 - 10X_3) + \ldots\Big] \quad (4c)\end{aligned}$$

$$k_4 = \frac{1}{16}\alpha^4\Big[1 - \alpha^2 X_1 + \frac{1}{8}\alpha^4(2X_1^2 - 5X_2) + \ldots\Big] \quad (4d)$$

$$k_5 = \frac{1}{32}\alpha^5\Big[1 - \frac{5}{4}\alpha^2 X_1 + \ldots\Big] \quad (4e)$$

$$k_6 = \frac{1}{64}\alpha^6\Big[1 - \ldots\Big] \quad (4f)$$

The moduli of the complex quantities k_1 to k_6 are required in equation (1). Substituting $(\phi_n - j\psi_n)$ for X_n, the squares of the moduli may be calculated and are given below to the order of α^8.

$$\begin{aligned} |k_1|^2 = \frac{1}{4}\alpha^2\Big[&1 - \frac{1}{2}\phi_1\alpha^2 + \frac{1}{16}\alpha^4(3\phi_1^2 - \psi_1^2 - 2\phi_2) \\ &+ \frac{1}{32}\alpha^6(4\phi_1\phi_2 - 2\psi_1\psi_2 - 2\phi_1^3 + 2\phi_1\psi_1^2 \\ &- \phi_3) + \ldots\Big] \quad (5a)\end{aligned}$$

$$|k_2|^2 = \frac{1}{16}\alpha^4\Big[1 - \phi_1\alpha^2 + \alpha^4\Big(\frac{1}{2}\phi_1^2 - \frac{3}{8}\phi_2\Big) + \ldots\Big] \quad (5b)$$

$$|k_3|^2 = \frac{1}{64}\alpha^6\Big[1 - \frac{3}{2}\alpha^2\phi_1 + \ldots\Big] \quad (5c)$$

$$|k_4|^2 = \frac{1}{256}\alpha^8\Big[1 - \ldots\Big] \quad (5d)$$

Substituting these values into equation (1), we have

$$\begin{aligned} R'/R = 1 + \frac{1}{8}x^2\Big[&\psi_2 + \alpha^2\psi_1 + \frac{1}{8}\alpha^4(\psi_2 - 4\phi_1\psi_1) \\ &+ \frac{1}{48}\alpha^6(\psi_3 - 6\phi_1\psi_2 + 9\phi_1^2\psi_1 - 3\psi_1^3 - 6\phi_2\psi_1) \\ &+ \frac{1}{256}\alpha^8(32\phi_1\phi_2\psi_1 - 16\psi_1^2\psi_2 - 16\phi_1^3\psi_1 + 16\phi_1\psi_1^3 \\ &- 8\phi_3\psi_1 + 16\phi_1^2\psi_2 - 12\phi_2\psi_2 - 8\phi_1\psi_3 + \psi_4) + \ldots\Big] \quad (6)\end{aligned}$$

which may be rewritten in the form

$$R'/R = 1 + F(x) + \sum_1^{\infty}\alpha^{2n}f_n(x) \quad (7)$$

where

$$F(x) = x^2\psi_2/8 \quad (7a)$$

$$f_1(x) = x^2\psi_1/8 \quad (7b)$$

$$f_2(x) = x^2(\psi_2 - 4\phi_1\psi_1)/64 \quad (7c)$$

$$f_3(x) = x^2(\psi_3 - 6\phi_1\psi_2 + 9\phi_1^2\psi_1 - 3\psi_1^3 - 6\phi_2\psi_1)/384 \quad (7d)$$

$$\begin{aligned} f_4(x) = x^2(&32\phi_1\phi_2\psi_1 - 16\psi_1^2\psi_2 - 16\phi_1^3\psi_1 \\ &+ 16\phi_1\psi_1^3 - 8\phi_3\psi_1 + 16\phi_1^2\psi_2 \\ &- 12\phi_2\psi_2 - 8\phi_1\psi_3 + \psi_4)/2048 \quad (7e)\end{aligned}$$

$F(x)$ is the increase of resistance of the conductor due to skin effect when the return conductor is remote ($\alpha = 0$).

When x or α or both are small, only a few terms in α need to be evaluated in order to obtain the value of R'/R to high accuracy, but when both x and α are large a very great number of terms must be evaluated, since the convergence of the series in equation (7) is then extremely slow. This equation is not, therefore, satisfactory for evaluating R'/R. A more convergent series is obtained by rewriting it in the form of equation (8), namely

$$R'/R = 1 + F(x) + \frac{\alpha^2 G(x)}{1 - \sum_1^{\infty}\alpha^{2n}g_n(x)} \quad (8)$$

where

$$G(x) = f_1(x) = x^2\psi_1/8 \quad (8a)$$

$$g_1(x) = \frac{f_2(x)}{f_1(x)} = \frac{\psi_2}{8\psi_1} - \frac{1}{2}\phi_1 \quad (8b)$$

$$\begin{aligned} g_2(x) &= \frac{f_3(x)}{f_1(x)} - [g_1(x)]^2 \\ &= \frac{1}{16}\Big(\frac{\psi_3}{3\psi_1} - 2\phi_2 - \psi_1^2 - \phi_1^2 - \frac{\psi_2^2}{4\psi_1^2}\Big) \quad (8c)\end{aligned}$$

$$\begin{aligned} g_3(x) &= \frac{f_4(x)}{f_1(x)} - [g_1(x)]^3 - 2g_1(x)g_2(x) \\ &= \frac{1}{32}\Big(\frac{\psi_4}{8\psi_1} - \frac{3}{2}\psi_1\psi_2 - \phi_3 - \frac{\phi_1^2\psi_2}{2\psi_1} - \frac{\phi_2\psi_2}{2\psi_1} \\ &\quad - \frac{\phi_1\psi_3}{3\psi_1} + \frac{\phi_1\psi_2^2}{4\psi_1^2} + \frac{\psi_2^3}{16\psi_1^3} - \frac{\psi_2\psi_3}{6\psi_1^2}\Big) \quad (8d)\end{aligned}$$

etc.

Butterworth's final solution consisted of equation (8), neglecting all terms above $g_1(x)$. In this paper it is proposed to carry the solution as far as $g_6(x)$. The terms above $g_1(x)$ will only affect the value of R'/R appreciably for values of α near to unity, where α^n decreases slowly as n increases. Equation (8) may therefore be rewritten with little error in the form:—

$$R'/R = 1+F(x)+\alpha^2G(x)/\{1-\alpha^2g_1(x)-\alpha^4[g_2(x)+g_3(x)] -\alpha^9[g_4(x)+g_5(x)+g_6(x)]-\ldots\}$$

Let
$$A(x) = g_1(x) = \frac{\psi_2}{8\psi_1} - \frac{\phi_1}{2} \quad . \quad . \quad . \quad (9a)$$

$$\begin{aligned} B(x) &= g_2(x) + g_3(x) \\ &= \frac{\psi_4}{256\psi_1} + \frac{\psi_3(2-3\phi_1)}{96\psi_1} - \frac{\psi_2(\phi_1^2+\phi_2)}{64\psi_1} \\ &\quad + \frac{\psi_2^2(\phi_1-2)}{128\psi_1^2} + \frac{\psi_2^3}{512\psi_1^3} - \frac{\phi_1^2}{16} - \frac{\psi_1^2}{16} - \frac{\phi_2}{8} \\ &\quad - \frac{3\psi_1\psi_2}{64} - \frac{\phi_3}{32} - \frac{\psi_2\psi_3}{192\psi_1} \quad . \quad . \quad . \quad . \quad (9b) \end{aligned}$$

$$C(x) = g_4(x) + g_5(x) + g_6(x) \quad . \quad . \quad (9c)$$

Then, ignoring all terms above $g_6(x)$, we have, approximately,

$$R'/R = 1+F(x)+\alpha^2G(x)/[1-\alpha^2A(x)-\alpha^4B(x)-\alpha^9C(x)] \quad (9)$$

The evaluation of the function $C(x)$ in terms of ϕ_n and ψ_n is exceedingly laborious. Fortunately, a simplification is possible, since $C(x)$ will only affect the value of R'/R appreciably for large values of x. In another paper,* Butterworth gives these asymptotic equations for ϕ_n and ψ_n as $x \rightarrow \infty$. They are:—

$$\begin{aligned} \phi_n &= -1+\frac{n\sqrt{2}}{x} - \frac{n\sqrt{2}(2n-1)(2n-3)}{8x^3} \\ &\quad -\frac{n(2n-1)(2n-3)}{4x^4} + \frac{n\sqrt{2}(2n-1)(4n^2-9)(2n-7)}{128x^5} \\ &\quad + \ldots \quad . \quad (10) \end{aligned}$$

$$\begin{aligned} \psi_n &= \frac{n\sqrt{2}}{x} - \frac{n(2n-1)}{x^2} + \frac{n\sqrt{2}(2n-1)(2n-3)}{8x^3} \\ &\quad + \frac{n\sqrt{2}(2n-1)(4n^2-9)(2n-7)}{128x^5} + \ldots \quad . \quad (11) \end{aligned}$$

Substituting these values into equations (4), and then calculating the moduli, we have, to the order of α^{12} and x^{-2},

$$\begin{aligned} |k_1|^2 &= \frac{1}{4}\alpha^2\Bigg[\left(1+\frac{1}{2}\alpha^2+\frac{5}{16}\alpha^4+\frac{7}{32}\alpha^6+\frac{21}{128}\alpha^8 + \frac{33}{256}\alpha^{10}+\ldots\right) - \frac{\sqrt{2}}{x}\left(\frac{1}{2}\alpha^2+\frac{5}{8}\alpha^4 + \frac{21}{32}\alpha^6+\frac{21}{32}\alpha^8+\frac{165}{256}\alpha^{10}+\ldots\right) \\ &\quad + \frac{2}{x^2}\left(\frac{1}{8}\alpha^4+\frac{1}{4}\alpha^6+\frac{23}{64}\alpha^8+\frac{29}{64}\alpha^{10}+\ldots\right) - \ldots\Bigg] \end{aligned}$$

$$\begin{aligned} |k_2|^2 &= \frac{1}{16}\alpha^4\Bigg[\left(1+\alpha^2+\frac{7}{8}\alpha^4+\frac{3}{4}\alpha^6+\frac{165}{256}\alpha^8+\ldots\right) \\ &\quad - \frac{\sqrt{2}}{x}\left(\alpha^2+\frac{7}{4}\alpha^4+\frac{9}{4}\alpha^6+\frac{165}{64}\alpha^8+\ldots\right) \\ &\quad + \frac{2}{x^2}\left(\frac{1}{2}\alpha^4+\frac{5}{4}\alpha^6+\frac{67}{32}\alpha^8+\ldots\right) - \ldots\Bigg] \end{aligned}$$

$$\begin{aligned} |k_3|^2 &= \frac{1}{64}\alpha^6\Bigg[\left(1+\frac{3}{2}\alpha^2+\frac{27}{16}\alpha^4+\frac{55}{32}\alpha^6+\ldots\right) \\ &\quad - \frac{\sqrt{2}}{x}\left(\frac{3}{2}\alpha^2+\frac{27}{8}\alpha^4+\frac{165}{32}\alpha^6+\ldots\right) \\ &\quad + \frac{2}{x^2}\left(\frac{9}{8}\alpha^4+\frac{27}{8}\alpha^6+\ldots\right) - \ldots\Bigg] \end{aligned}$$

$$\begin{aligned} |k_4|^2 &= \frac{1}{256}\alpha^8\Bigg[\left(1+2\alpha^2+\frac{11}{4}\alpha^4+\ldots\right) \\ &\quad - \frac{\sqrt{2}}{x}\left(2\alpha^2+\frac{11}{2}\alpha^4+\ldots\right) + \frac{2}{x^2}(2\alpha^4+\ldots) - \ldots\Bigg] \end{aligned}$$

$$\begin{aligned} |k_5|^2 &= \frac{1}{1024}\alpha^{10}\Bigg[\left(1+\frac{5}{2}\alpha^2+\ldots\right) \\ &\quad - \frac{\sqrt{2}}{x}\left(\frac{5}{2}\alpha^2+\ldots\right) + \ldots\Bigg] \end{aligned}$$

$$|k_6|^2 = \frac{\alpha^{12}}{4096} + \ldots$$

Equation (1) may now be written in the form:—

$$\begin{aligned} \frac{R'}{R} &= 1 + F(x) + \alpha^2\left(\frac{x}{4\sqrt{2}} - \frac{1}{8} - \frac{1}{32\sqrt{2}x} - \ldots\right) \\ &\quad + \alpha^4\left(\frac{3x}{16\sqrt{2}} - \frac{9}{32} + \frac{17}{128\sqrt{2}x} + \ldots\right) \\ &\quad + \alpha^6\left(\frac{5x}{32\sqrt{2}} - \frac{25}{64} + \frac{115}{256\sqrt{2}x} + \ldots\right) \\ &\quad + \alpha^8\left(\frac{35x}{256\sqrt{2}} - \frac{245}{512} + \frac{1785}{2048\sqrt{2}x} + \ldots\right) \\ &\quad + \alpha^{10}\left(\frac{63x}{512\sqrt{2}} - \frac{567}{1024} + \frac{5649}{4096\sqrt{2}x} + \ldots\right) \\ &\quad + \alpha^{12}\left(\frac{231x}{2048\sqrt{2}} - \frac{2541}{4096} + \frac{32109}{16384\sqrt{2}x} + \ldots\right) \\ &\quad + \ldots \\ &= 1 + F(x) + \alpha^2G(x)/[1 - \sum_1^\infty \alpha^{2n}g_n(x)] \quad . \quad . \quad (12) \end{aligned}$$

whence

$$G(x) = \frac{x}{4\sqrt{2}} - \frac{1}{8} - \frac{1}{32\sqrt{2}x} - \ldots \quad . \quad . \quad . \quad (13)$$

$$g_1(x) = \frac{3}{4} - \frac{3}{2\sqrt{2}x} - \frac{1}{8x^2} - \ldots \quad . \quad . \quad . \quad (13a)$$

$$g_2(x) = \frac{1}{16} - \frac{1}{4\sqrt{2}x} - \frac{5}{16x^2} + \ldots \quad . \quad . \quad . \quad (13b)$$

$$g_3(x) = \frac{1}{32} - \frac{3}{16\sqrt{2}x} - \frac{19}{64x^2} + \ldots \quad . \quad . \quad . \quad (13c)$$

$$g_4(x) = \frac{5}{256} - \frac{5}{32\sqrt{2}x} - \frac{37}{128x^2} + \ldots \quad . \quad . \quad (13d)$$

$$g_5(x) = \frac{7}{512} - \frac{35}{256\sqrt{2}x} - \frac{291}{1024x^2} + \ldots \quad . \quad . \quad (13e)$$

* See Bibliography, (10)

Equations (13), (13*a*), (13*b*), and (13*c*), may also be obtained directly, by inserting asymptotic values of ϕ_n and ψ_n into equations (8*a*), (8*b*), (8*c*), and (8*d*).

At still higher values of x, when the first term only is of importance, $F(x) = x/(2\sqrt{2})$, approximately, and equation (12) becomes

$$\frac{R'}{R} = \frac{x}{2\sqrt{2}}\left(1 + \frac{1}{2}\alpha^2 + \frac{3}{8}\alpha^4 + \frac{5}{16}\alpha^6 + \frac{35}{128}\alpha^8 + \frac{63}{256}\alpha^{10} + \frac{231}{1024}\alpha^{12} + \ldots\right)$$

This series can be recognized as corresponding to the expansion of $(1 - \alpha^2)^{-\frac{1}{2}}$, so that, for very high values of x,

$$R'/R = x/\left[8(1 - \alpha^2)\right]^{\frac{1}{2}} \quad . \quad . \quad . \quad (14)$$

Equation (14) is the formula put forward by Snow and Strutt. It is very simple, but for finite values of x it may be seriously in error. It is useful, however, for estimating the limiting errors of equation (9) when $x \to \infty$. The errors of equation (9) for values of x less than ∞ will, in general, be less than the errors when $x = \infty$.

Equation (14) may also be used for determining the first term of $g_6(x)$. The second and third terms may be estimated by extrapolation from the second and third terms of $g_1(x)$, $g_2(x)$, $g_3(x)$, $g_4(x)$, and $g_5(x)$. We then have approximately,

$$g_6(x) = \frac{21}{2048} - \frac{1}{8\sqrt{2x}} - \frac{9}{32x^2} + \ldots \quad . \quad (13f)$$

The fourth term of $g_4(x)$, $g_5(x)$, and $g_6(x)$, is positive. This may be allowed for, to some extent, by slightly reducing the value of the third term. Combining $g_4(x)$, $g_5(x)$, and $g_6(x)$, and slightly altering the value of the terms, in order to simplify the fractions, we have

$$\begin{aligned} C(x) &= g_4(x) + g_5(x) + g_6(x) \\ &= \frac{1}{23} - \frac{8}{27x} - \frac{3}{4x^2} \quad . \quad . \quad . \quad . \quad (15) \end{aligned}$$

By equation (15), $C(x)$ falls to zero when x falls to $8 \cdot 8$. For values of x less than $8 \cdot 8$, $C(x)$ should be taken equal to zero. When $x \to \infty$, equation (9) becomes

$$\frac{R'}{R} = \frac{x}{2\sqrt{2}}\left[1 + \frac{\alpha^2}{2\left(1 - \frac{3}{4}\alpha^2 - \frac{3}{32}\alpha^4 - \frac{1}{23}\alpha^9\right)}\right] \quad . \quad (16)$$

If equation (16) is compared with the rigid equation (14), it is found that its error is less than 1 per cent for all values of α less than $0 \cdot 92$.

As x decreases from ∞ the range of validity of equation (9) for 1 per cent accuracy increases, and when x falls to about 10, equation (9) is less than 1 per cent in error for values of α up to unity. In practical cases, α will usually be less than $0 \cdot 92$, but if, in an exceptional case, it should be greater than $0 \cdot 92$, it is possible to correct equation (9) by means of a correction factor. The development of this correction factor is given in Appendix 1. In the next section, formulæ are given for the rapid evaluation of the functions $F(x)$, $G(x)$, $A(x)$, and $B(x)$. For the range of the argument where these formulæ fail, tables are given at intervals of the argument sufficiently close to allow of linear interpolation.

(3) The Functions $F(x)$, $G(x)$, $A(x)$, and $B(x)$.

Butterworth* has developed equations for evaluating ϕ_n and ψ_n for any value of x. For very small values of x these equations take the form given below, namely

$$\phi_n = \frac{-2x^4}{(2n)^2(2n+2)(2n+4)} + \frac{(28n+48)x^8}{(2n)^4(2n+2)^2(2n+4)(2n+6)(2n+8)} - \ldots \quad (17)$$

$$\psi_n = \frac{x^2}{2n(2n+2)} - \frac{(10n+12)x^6}{(2n)^3(2n+2)^2(2n+4)(2n+6)} + \ldots \quad (18)$$

For large values of x, equations (10) and (11) may be used. If these values are substituted into the equations for the functions $F(x)$, etc., asymptotic equations are obtained covering the range of the argument near zero and near ∞. There remains a range of the argument which is not covered. For this range, the values of the functions are given in Table 1 for sufficiently close intervals of the argument to allow of linear interpolation.

(i) $F(x)$.

$$F(x) = x^2\psi_2/8 \quad . \quad . \quad . \quad . \quad . \quad (7a)$$

For small values of x,

$$\begin{aligned} F(x) &= \frac{x^4}{192}\left[1 - \frac{x^4}{240}(1 - \ldots)\right] \\ &= \frac{5x^4}{960 + 4x^4} \text{ approximately} \quad . \quad . \quad (19) \end{aligned}$$

Equation (19) may be used for all values of x from 0 up to $2 \cdot 2$ with an error of less than $0 \cdot 1$ per cent.

For large values of x,

$$F(x) = \frac{x}{2\sqrt{2}}\left(1 + \frac{3}{8x^2}\right) - \frac{3}{4} \quad . \quad . \quad . \quad . \quad (20)$$

Equation (20) gives $F(x)$ with an error of less than $0 \cdot 02$ per cent for values of x above 6.

(ii) $G(x)$.

$$G(x) = x^2\psi_1/8 \quad . \quad . \quad . \quad . \quad . \quad . \quad (8a)$$

For small values of x,

$$\begin{aligned} G(x) &= \frac{x^4}{64} - \frac{11x^8}{24576} + \ldots \\ &= \frac{6x^4}{384 + 11x^4} \text{ approximately.} \end{aligned}$$

By calculating a few actual values it is found that a slight improvement in this approximate formula may be

* See Bibliography, (10).

TABLE 1.

x	$F(x)$	$G(x)$	$A(x)$	$B(x)$
1·4	$\frac{5x^4}{960+4x^4}$	$\frac{11x^4}{704+20x^4}$	$\frac{1}{24}+\frac{8x^4}{700+19x^4}$	— 0·0010
1·5				— 0·0018
1·6				— 0·0025
1·7		0·1055	0·1196	— 0·0034
1·75		0·1158	0·1272	— 0·0039
1·8		0·1265	0·1352	— 0·0043
1·85		0·1375	0·1435	— 0·0047
1·9		0·1489	0·1520	— 0·0052
1·95		0·1605	0·1608	— 0·0056
2		0·1724	0·1698	— 0·0060
2·05		0·1845	0·1789	— 0·0064
2·1		0·1967	0·1882	— 0·0068
2·15		0·2090	0·1976	— 0·0071
2·2	0·1113	0·2214	0·2070	— 0·0074
2·22	0·1150	0·2264	0·2108	— 0·0075
2·24	0·1188	0·2313	0·2146	— 0·0076
2·26	0·1227	0·2363	0·2184	— 0·0078
2·28	0·1267	0·2412	0·2222	— 0·0079
2·30	0·1307	0·2462	0·2260	— 0·0080
2·32	0·1348	0·2511	0·2298	— 0·0081
2·34	0·1390	0·2561	0·2336	— 0·0082
2·36	0·1433	0·2610	0·2373	— 0·0083
2·38	0·1477	0·2659	0·2411	— 0·0084
2·40	0·1521	0·2708	0·2449	— 0·0085
2·42	0·1566	0·2756	0·2486	— 0·0086
2·44	0·1612	0·2805	0·2523	— 0·0087
2·46	0·1659	0·2853	0·2561	— 0·0088
2·48	0·1716	0·2901	0·2598	— 0·0088
2·50	0·1754	0·2949	0·2635	— 0·0089
2·52	0·1803	0·2996	0·2672	— 0·0089
2·54	0·1853	0·3043	0·2709	— 0·0090
2·56	0·1903	0·3090	0·2745	— 0·0090
2·58	0·1954	0·3137	0·2782	— 0·0090
2·60	0·2006	0·3184	0·2818	— 0·0091
2·62	0·2059	0·3230	0·2854	— 0·0091
2·64	0·2112	0·3276	0·2889	— 0·0091
2·66	0·2166	0·3321	0·2925	— 0·0091
2·68	0·2220	0·3367	0·2960	— 0·0091
2·70	0·2275	0·3412	0·2995	— 0·0090
2·75	0·2417	0·3523	0·3081	— 0·0090
2·8	0·2562	0·3632	0·3166	— 0·0090
2·85	0·2711	0·3739	0·3249	— 0·0089
2·9	0·2864	0·3844	0·3330	— 0·0087
2·95	0·3021	0·3948	0·3409	— 0·0085
3	0·3181	0·4050	0·3487	— 0·0083
3·05	0·3344	0·4150	0·3563	— 0·0080
3·1	0·3510	0·4248	0·3636	— 0·0077
3·15	0·3679	0·4345	0·3708	— 0·0074
3·2	0·3850	0·4440	0·3779	— 0·0070
3·25	0·4024	0·4533	0·3847	— 0·0066
3·3	0·4200	0·4626	0·3914	— 0·0062
3·35	0·4378	0·4717	0·3978	— 0·0057
3·4	0·4557	0·4808	0·4041	— 0·0052
3·45	0·4738	0·4897	0·4102	— 0·0047
3·5	0·4920	0·4986	0·4161	— 0·0042

TABLE 1 (*continued*).

x	$F(x)$	$G(x)$	$A(x)$	$B(x)$
3·55	0·5104	0·5073	0·4219	— 0·0036
3·6	0·5288	0·5160	0·4275	— 0·0030
3·65	0·5473	0·5247	0·4329	— 0·0024
3·7	0·5659	0·5333	0·4382	— 0·0018
3·75	0·5845	0·5418	0·4433	— 0·0012
3·8	0·6031	0·5503	0·4482	— 0·0006
3·85	0·6218	0·5588	0·4530	+ 0·0001
3·9	0·6405	0·5673	0·4577	0·0008
3·95	0·6592	0·5758	0·4622	0·0015
4	0·6779	0·5842	0·4665	0·0022
4·05	0·6966	0·5926	0·4707	0·0029
4·1	0·7152	0·6010	0·4748	0·0036
4·15	0·7338	0·6094	0·4788	0·0044
4·2	0·7523	0·6179	0·4827	0·0052
4·3	0·7893	0·6348	0·4900	0·0067
4·4	0·8261	0·6518	0·4969	0·0083
4·5	0·8627	0·6688	0·5034	0·0098
4·6	0·8991	0·6858	0·5095	0·0114
4·7	0·9353	0·7030	0·5152	0·0130
4·8	0·9713	0·7203	0·5206	0·0146
4·9	1·0071	0·7376	0·5258	0·0161
5	1·0427	0·7550	0·5306	0·0176
5·1	1·0781	0·7727	0·5351	0·0191
5·2	1·1135	0·7904	0·5395	0·0205
5·3	1·1487	0·8081	0·5436	0·0219
5·4	1·1839	0·8258	0·5476	0·0233
5·5	1·2189	0·8435	0·5514	0·0247
5·6	1·2539	0·8613	0·5551	0·0260
5·7	1·2889	0·8790	0·5587	0·0273
5·8	1·3238	0·8967	0·5621	0·0286
5·9	1·3587	0·9144	0·5654	0·0299
6	1·3936	0·9322	0·5686	0·0311
6·2	1·4634	0·9676	0·5746	0·0333
6·4	1·5332	1·0031	0·5802	0·0353
6·6	1·6031	1·0385	0·5855	0·0372
6·8	1·6731	1·0740	0·5904	0·0390
7	1·7432	1·1094	0·5951	0·0408
7·2	1·8133	1·1448	0·5995	0·0424
7·4	1·8836	1·1802	0·6037	0·0439
7·6	1·9538	1·2157	0·6077	0·0454
7·8	2·0241	1·2511	0·6114	0·0468
8	2·0945	1·2865	0·6149	0·0481
8·2	2·1648	1·3219	0·6183	0·0493
8·4	2·2352	1·3573	0·6215	0·0505
8·6	2·3056	1·3928	0·6246	0·0516
8·8	2·3760	1·4282	0·6275	0·0526
9	2·4464	1·4636	0·6302	0·0536
9·2	2·5168	1·4990	0·6329	0·0545
9·4	2·5872	1·5344	0·6354	0·0555
9·6	2·6577	1·5698	0·6378	0·0564
9·8	2·7281	1·6052	0·6402	0·0572
10	2·7986	1·6406	0·6424	0·0580
10·5	2·9748	1·7291	0·6476	0·0599
11	3·1510	1·8176	0·6523	0·0616
11·5	3·3273	1·9061	0·6566	0·0631
12	3·5036	1·9945	0·6606	0·0644

effected by reducing the coefficient of x^4 in the denominator by 0·8 per cent. We then have

$$G(x) = \frac{6x^4}{384 + \frac{120}{11}x^4}$$

$$= \frac{11x^4}{704 + 20x^4} \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Equation (21) may be used for all values of x from 0 to 1·7 with an error of less than 0·05 per cent. For large values of x,

$$G(x) = \frac{x}{4\sqrt{2}}\left(1 - \frac{1}{8x^2}\right) - \frac{1}{8} \quad . \quad . \quad (22)$$

Equation (22) may be used for all values of x above 5 with an error of less than 0·05 per cent.

(iii) $A(x)$.

$$A(x) = \frac{\psi_2}{8\phi_1} - \frac{\phi_1}{2} \quad . \quad . \quad . \quad . \quad . \quad (9a)$$

For small values of x,

$$A(x) = \frac{1}{24} + \frac{527x^4}{46080} + \ldots$$

Following similar methods to those employed in obtaining formulæ for $F(x)$ and $G(x)$, the following approximate formula is obtained for $A(x)$.

$$A(x) = \frac{1}{24} + \frac{8x^4}{700 + 19x^4} \quad . \quad . \quad . \quad (23)$$

Equation (23) may be used for all values of x less than 1·7 with an error of less than 0·1 per cent. For large values of x,

$$A(x) = \frac{3}{4} - \frac{3}{2\sqrt{2x}} - \frac{1}{8x^2} - \frac{5}{16\sqrt{2x^3}} - \frac{13}{32x^4} - \ldots$$

This formula is valid for values of x above 5, but, as it is rather long, values of $A(x)$ are given in Table 1 for values of x up to 12. For values of x above 12, the following equation may be used with an error of less than 0·03 per cent.

$$A(x) = \frac{75x - 107}{100x} \quad . \quad . \quad . \quad . \quad (24)$$

(iv) $B(x)$.

$$B(x) = \frac{\psi_4}{256\psi_1} + \frac{\psi_3(2 - 3\phi_1)}{96\psi_1} - \frac{\psi_2(\phi_1^2 + \phi_2)}{64\psi_1} + \frac{\psi_2^2(\phi_1 - 2)}{128\psi_1^2} + \frac{\psi_2^3}{512\psi_1^3} - \frac{\phi_1^2}{16} - \frac{\psi_1^2}{16} - \frac{\phi_2}{8} - \frac{3\psi_1\psi_2}{64} - \frac{\phi_3}{32} - \frac{\psi_2\psi_3}{192\psi_1} \quad . \quad . \quad (9b)$$

For values of x up to 1·4, $B(x)$ is less than 0·001 and may be neglected. For large values of x,

$$B(x) = \frac{3}{32} - \frac{17}{16\sqrt{2x}} - \frac{39}{64x^2} + \frac{219}{128\sqrt{2x^3}} + \ldots$$

This may be replaced by a simpler formula, namely

$$B(x) = \frac{3}{32}\left[1 - \frac{33}{10x}\left(1 + \frac{2}{x} - \frac{4}{x^2}\right)\right] \quad . \quad (25)$$

Equation (25) may be used for values of x above 9 with an error of less than 0·2 per cent.

(4) Working Formula.

The formula developed in this paper, namely

$$R'/R = 1 + F(x) + \alpha^2G(x)/[1 - \alpha^2A(x) - \alpha^4B(x) - \alpha^9C(x)] \quad (9)$$

has an error of less than 1 per cent for all values of x if α is less than 0·92, and for all values of α if x is less than 10.

For small values of x.

$F(x) = 5x^4/(960 + 4x^4)$, if x is less than 2·2 . . (19)

$G(x) = 11x^4/(704 + 20x^4)$, if x is less than 1·7 . (21)

$A(x) = \frac{1}{24} + 8x^4/(700 + 19x^4)$, if x is less than 1·7 (23)

$B(x) = 0$, if x is less than 1·4

$C(x) = 0$, if x is less than 8·8

For large values of x.

$$F(x) = \frac{x}{2\sqrt{2}}\left(1 + \frac{3}{8x^2}\right) - \frac{3}{4}, \text{ if } x \text{ is greater than } 6 \quad (20)$$

$$G(x) = \frac{x}{4\sqrt{2}}\left(1 - \frac{1}{8x^2}\right) - \frac{1}{8}, \text{ if } x \text{ is greater than } 5 \quad (22)$$

$$A(x) = \frac{75x - 107}{100x}, \text{ if } x \text{ is greater than } 12 \quad . \quad . \quad (24)$$

$$B(x) = \frac{3}{32}\left[1 - \frac{33}{10x}\left(1 + \frac{2}{x} - \frac{4}{x^2}\right)\right], \text{ if } x \text{ is greater than } 9 \quad . \quad . \quad . \quad (25)$$

$$C(x) = \frac{1}{23} - \frac{8}{27x} - \frac{3}{4x^2}, \text{ if } x \text{ is greater than } 8{\cdot}8 \quad (15)$$

For intermediate values of x, the values of $F(x)$, $G(x)$, $A(x)$, and $B(x)$, may be obtained from Table 1.

(5) Experimental Work.

The accuracy of equation (9) was checked by a series of measurements on two copper rods, each 1·26 in. diameter and 12 ft. long. The principle of the bridge employed for measuring the alternating-current resistance of the rods is shown in Fig. 1.

The inductive component of the voltage-drop across the unknown impedance, Z, is balanced against the secondary e.m.f. of a variable mutual inductance, M, whose primary carries the same current as Z. The resistance component of the voltage-drop is balanced against a fraction of the voltage-drop across a four-terminal resistance, R_1, carrying the secondary current of a current transformer T, whose primary is in series with Z. r_1 is the total resistance of a Thomson–Varley potential divider, and r_2 is the resistance between tapping points. The fraction of the voltage across R_1 which is tapped off, r_2/r_1, may be varied from 0·00002 up to 0·99998. The galvanometer deflection is reduced to zero by varying M and r_2, and at balance no current is taken from the voltage terminals of Z.

Let

$$Z = R' + j\omega L'$$

where R' denotes the alternating-current resistance of Z and $\omega L'$ denotes the alternating-current reactance of Z.

Let

$$\frac{\text{Secondary current of } T}{\text{Primary current of } T} = \frac{1 + j\theta}{K}$$

where θ = phase angle of T, and K = ratio of T.

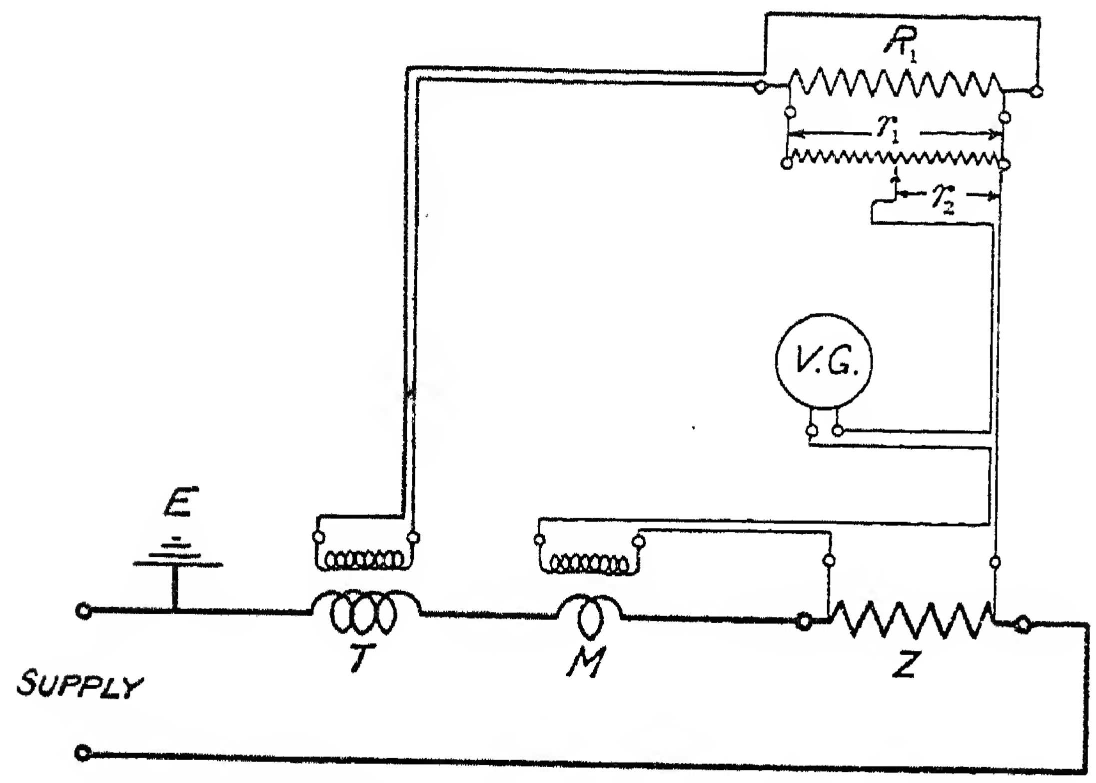

FIG. 1.—Alternating-current bridge for measurement of low impedances.

E = earth point; T = current transformer; M = mutual inductance; Z = impedance to be measured; V.G. = vibration galvanometer; R_1 = 4-terminal resistance; r_1 = Thomson–Varley potential divider; r_2 = tapped-off portion of divider.

Let

$$\frac{\text{Secondary e.m.f. of } M}{\text{Primary current of } M} = \omega M(\sigma + j)$$

where σ = phase defect of M.

Let

$$\text{Impedance of } R_1 = R_1(1 + j\gamma)$$
$$\text{Impedance of } r_1 = r_1(1 + j\delta)$$
$$\text{Impedance of } r_2 = r_2(1 + j\eta)$$

where γ, δ, and η, are phase angles of R_1, r_1, and r_2 respectively.

It will be assumed that the residual errors of T, M, R_1, r_1, and r_2, are so small that their products may be neglected. Then the equation of balance is

$$R' + j\omega L' - \omega M(\sigma + j) = \frac{r_2 R_1(1 + j\theta)(1 + j\gamma)(1 + j\eta)}{[r_1(1 + j\delta) + R_1(1 + j\gamma)]K}$$
$$= \frac{r_2 R_1}{(r_1 + R_1)K}\left[1 + j\left(\theta + \gamma + \eta - \frac{\delta r_1 + \gamma R_1}{r_1 + R_1}\right)\right]$$

Equating in-phase components,

$$R' = \frac{r_2 R_1}{(r_1 + R_1)K} + \omega M\sigma \quad . \quad . \quad . \quad (26)$$

The phase defect of the mutual inductance is, therefore, the only error which has a first-order effect upon the measured value of R'. The mutual inductance employed consisted of a uniformly wound toroid which was nearly astatic to external fields and which had a phase defect of approximately 0·4 minute at a frequency of 600 cycles per sec., the highest frequency used. The maximum value of $\omega M\sigma/R'$ was 0·3 per cent. This value was reached at a frequency of 600 cycles per sec. and with the conductors spaced far apart ($a = 0{\cdot}1547$). The error was less at closer spacings and also at lower frequencies, and was therefore small enough to be neglected.

The d.c. resistance was measured by potentiometer with an accuracy of approximately 0·1 per cent. Fig. 2 shows the actual circuits employed, with the switching arrangements to allow the d.c. and a.c. measurements to be made in quick succession. The resistances of both conductors were measured on direct current and alternating current, and the mean values taken. Since the voltage leads from the ends of the two conductors were twisted up together, any e.m.f.'s induced in these leads by stray magnetic fields were equal. The voltage-drops in the two conductors were in opposite directions, and consequently the mean value of the two resistance measurements eliminated any error due to e.m.f.'s in

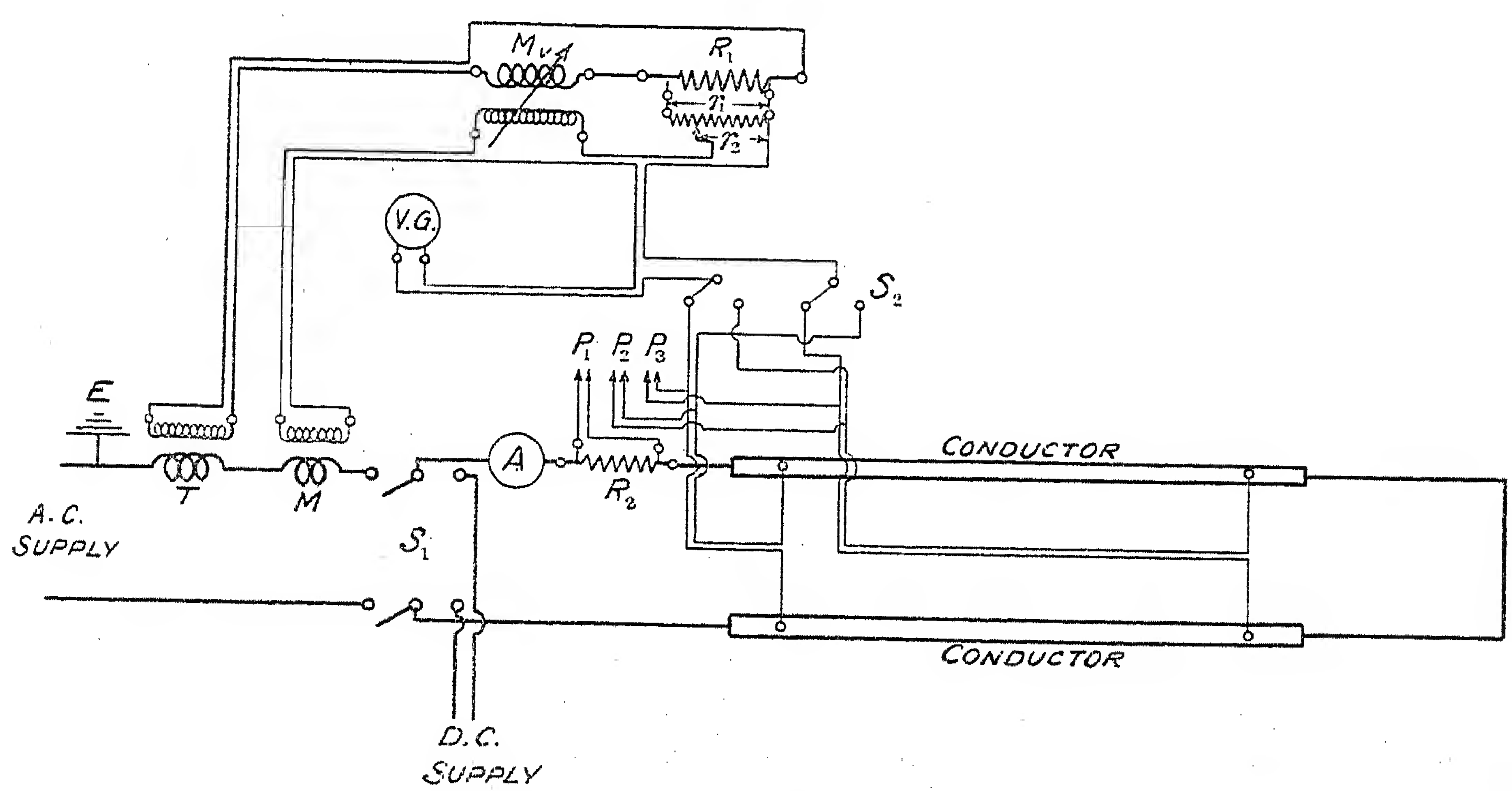

FIG. 2.—Circuits for measuring resistance of conductors with direct and with alternating current.

E = earth point; T = current transformer; M = mutual inductance; V.G. = vibration galvanometer; R_1 = 4-terminal resistance; r_1 = Thomson–Varley potential divider; r_2 = tapped-off portion of divider; S_1 = switch for changing over from d.c. to a.c. supply; S_2 = switch for connecting voltage terminals of either conductor to measuring circuit; M_v = variable mutual inductance; A = ammeter; R_2 = direct-current 4-terminal resistance; P_1, P_2, and P_3, indicate connections to three circuits of a d.c. potentiometer. Leads shown parallel and close together were twisted up together in the actual lay-out.

the voltage leads. Fig. 2 shows that two mutual inductances were employed to balance the quadrature component. The mutual inductance in series with the conductors could only be varied in steps, by altering the number of primary turns. The mutual inductance in the secondary circuit of the current transformer was of the continuously variable type and was used for the fine adjustment. An error was introduced into the measurements by the phase defect of this mutual inductance, and this was allowed for by means of a small correction. The frequency was measured by means of a sonometer similar to that described by A. E. Kennelly and C. H. Manneback.*

TABLE 2.

x	α	R'/R, computed by equation (9) (a)	R'/R, measured experimentally (b)	$\frac{(b)}{(a)}$
1·708	0·983	1·160	1·160	1·000
2·415	0·983	1·500	1·501	1·001
2·957	0·983	1·869	1·870	1·001
3·413	0·983	2·222	2·218	0·998
5·033	0·983	3·621	3·602	0·995
5·906	0·983	4·439	4·407	0·993
6·857	0·980	5·327	5·315	0·998
7·668	0·980	6·141	6·139	1·000
8·365	0·983	6·922	6·939	1·002
1·708	0·800	1·117	1·118	1·000
2·417	0·800	1·364	1·367	1·002
2·961	0·800	1·630	1·631	1·001
3·420	0·800	1·881	1·882	1·001
5·021	0·800	2·794	2·794	1·000
5·929	0·800	3·310	3·308	0·999
6·843	0·800	3·832	3·826	0·998
7·649	0·800	4·295	4·292	0·999
8·375	0·800	4·715	4·714	1·000
1·719	0·4028	1·062	1·063	1·001
2·430	0·4028	1·206	1·208	1·002
2·974	0·4028	1·378	1·378	1·000
3·432	0·4028	1·552	1·554	1·001
5·031	0·4028	2·189	2·196	1·003
5·901	0·4028	2·522	2·519	0·999
6·865	0·4028	2·891	2·890	1·000
7·665	0·4028	3·198	3·199	1·000
8·371	0·4028	3·469	3·468	1·000
1·713	0·1547	1·046	1·047	1·001
2·422	0·1547	1·164	1·164	1·000
2·965	0·1547	1·317	1·318	1·001
3·423	0·1547	1·476	1·479	1·002
5·027	0·1547	2·071	2·074	1·001
5·897	0·1547	2·378	2·381	1·001
6·871	0·1547	2·725	2·730	1·002
7·654	0·1547	3·003	3·007	1·001
8·375	0·1547	3·259	3·259	1·000

Measurements of the d.c. and a.c. resistance of these rods were made at frequencies from 25 up to 600 cycles per sec., corresponding to values of x from 1·7 up to 8·4, and at a number of different spacings of the conductors. The results are given in Table 2, and it may be seen that the maximum difference between the calculated value of R'/R and the measured value is 0·7 per cent. This may be considered to be satisfactory agreement.

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APPENDIX 1.

EVALUATION OF R'/R WHEN α IS GREATER THAN 0·92 AND x IS GREATER THAN 10.

Let the value of R'/R be given by equation (27), namely

$$\frac{R'}{R} = C\left[1 + F(x) + \frac{\alpha^2 G(x)}{1 - \alpha^2 A(x) - \alpha^4 B(x) - \alpha^9 C(x)}\right] \quad (27)$$

where C is a function to be determined.

When $x \to \infty$, equation (27) becomes

$$\frac{R'}{R} \to C_\infty \frac{x}{2\sqrt{2}}\left[1 + \frac{\alpha^2}{2\left(1 - \frac{3}{4}\alpha^2 - \frac{3}{32}\alpha^4 - \frac{1}{23}\alpha^9\right)}\right] . \quad (28)$$

where $C \to C_\infty$ as $x \to \infty$

From equations (14) and (28) we may write

$$\frac{1}{C_\infty} = \left(\frac{1}{1-\alpha^2}\right)^{\frac{1}{2}}\left[1 + \frac{\alpha^2}{2\left(1 - \frac{3}{4}\alpha^2 - \frac{3}{32}\alpha^4 - \frac{1}{23}\alpha^9\right)}\right] \quad (29)$$

Substituting $\beta = (1 - \alpha)$ into equation (29), and expanding, we have

$$C_\infty = \frac{1}{\sqrt{\beta}}(0\cdot1301 + 2\cdot379\beta - 7\cdot07\beta^2 + 27\cdot0\beta^3 - 103\beta^4 + \ldots)$$

$$= \frac{1}{100}\left(\frac{13}{\sqrt{\beta}} + \frac{238\sqrt{\beta}}{1 + 3\beta - 2\beta^2}\right) \text{ approximately} . \quad (30)$$

Now C is usually less than C_∞, and for values of x less than 10, C is very nearly equal to unity. As a first approximation, therefore, we may write,

$$C = 1 + (C_\infty - 1)\left(1 - \frac{10}{x}\right) \quad . \quad . \quad (31)$$

for all values of x above 10.

This is as far as it is possible to go without a more exhaustive analysis of equation (1) of this paper. Equation (31) gives finite values for C for all values of α except $\alpha = 1$. In practice, a value of α equal to unity could never be attained on account of the necessity of insulation between the two conductors, so that this limitation is not serious. The accuracy of equation (31) cannot be stated, but since it is possible to determine three values of R'/R, (a) without applying the correction factor, (b) applying the correction factor, and (c) applying the correction factor for $x = \infty$, the degree of uncertainty can be gauged to some extent.

APPENDIX 2.

Examples.

Three examples are worked out below to show the applications of the formulæ.

(1) *To find the value of R'/R for a system of go and return conductors, consisting of two $\frac{1}{2}$-in. diameter copper rods with a separation of $\frac{1}{4}$ in., at a frequency of 50 cycles per sec. Air temperature = 20° C.*

In this case, $\alpha = \frac{2}{3}$. Resistivity of copper $= 1\,724 \times 10^{-9}$ ohm per cm cube.

$$\therefore \quad R = \frac{1\,724 \times 10^{-9}}{\pi \times \frac{1}{16} \times 2\cdot54^2}$$

$$= 1\,360 \times 10^{-9} \text{ ohm}$$

$$x = 2(314\cdot2/1\,360)^{\frac{1}{2}} = 0\cdot961$$

$$F(x) = 5 \times 0\cdot961^4/(960 + 4 \times 0\cdot961^4) = 0\cdot00443$$

$$G(x) = 11 \times 0\cdot961^4/(704 + 20 \times 0\cdot961^4) = 0\cdot01303$$

$$A(x) = \frac{1}{24} + \frac{8 \times 0\cdot961^4}{700 + 19 \times 0\cdot961^4} = 0\cdot05121$$

$$B(x) = 0$$

$$C(x) = 0$$

$$R'/R = 1\cdot00443 + \frac{\frac{4}{9} \times 0\cdot01303}{1 - \frac{4}{9} \times 0\cdot05121}$$

$$= 1\cdot00443 + 0\cdot00593$$

$$= 1\cdot0104$$

(2) $x = 8\cdot365$, $\alpha = 0\cdot983$.

$$\left.\begin{aligned} F(x) &= 2\cdot1648 + 0\cdot0704 \times \frac{0\cdot165}{0\cdot200} = 2\cdot2229 \\ G(x) &= 1\cdot3219 + 0\cdot0354 \times \frac{0\cdot165}{0\cdot200} = 1\cdot3511 \\ A(x) &= 0\cdot6183 + 0\cdot0032 \times \frac{0\cdot165}{0\cdot200} = 0\cdot6209 \\ B(x) &= 0\cdot0493 + 0\cdot0012 \times \frac{0\cdot165}{0\cdot200} = 0\cdot0503 \end{aligned}\right\} \text{From Table 1}$$

$$C(x) = 0$$

$$\alpha^2 = 0\cdot9663; \quad \alpha^4 = 0\cdot9338$$

$$R'/R = 3\cdot2229 + \frac{1\cdot3056}{1 - 0\cdot6000 - 0\cdot0470}$$

$$= 3\cdot2229 + 3\cdot6986 = 6\cdot922$$

The experimentally-determined figure for this case was 6·939, showing a difference of 0·2 per cent.

(3) $x = 100$, $\alpha = 0\cdot95$.

For these values, equation (9) will be more than 1 per cent in error, so that the correction factor must be applied.

$$F(x) = \frac{100}{2\sqrt{2}} - \frac{3}{4} = 34\cdot6$$

$$G(x) = \frac{100}{4\sqrt{2}} - \frac{1}{8} = 17\cdot55$$

$$A(x) = \frac{(7\,500 - 107)}{10\,000} = 0\cdot7393$$

$$B(x) = \frac{3}{32}\left(1 - \frac{33}{1\,000}\right) = 0\cdot0907$$

$$C(x) = 0\cdot0435 - 0\cdot0030 = 0\cdot0405$$

$$\alpha^2 = 0\cdot9025, \quad \alpha^4 = 0\cdot815, \quad \alpha^9 = 0\cdot631$$

$$\beta = 0\cdot05$$

$$C_\infty = 0\cdot01\left(\frac{13}{\sqrt{0\cdot05}} + \frac{238\sqrt{0\cdot05}}{1 + 3 \times 0\cdot05 - 2 \times 0\cdot05^2}\right)$$

$$= 1\cdot046$$

$$C = 1 + 0\cdot046 \times 0\cdot9 = 1\cdot041$$

$$\frac{R'}{R} = 1\cdot041\left(35\cdot6 + \frac{15\cdot84}{1 - 0\cdot6672 - 0\cdot0739 - 0\cdot0255}\right)$$

$$= 1\cdot041 \times 103\cdot4 = 107\cdot6$$

Alternatively,

$$103\cdot4 < R'/R < 103\cdot4 \times C_\infty$$

$$\therefore \quad 103\cdot4 < R'/R < 108\cdot2$$

$$\therefore \quad R'/R = 105\cdot8 \pm 2\cdot3 \text{ per cent}$$

TESTS ON THE ELECTRIC AND MAGNETIC PROPERTIES OF ALUMINIUM-STEEL CORED CABLE.*

By J. A. CLEGG, M.Sc.(Eng.), Graduate.

(*Paper first received* 14*th May, and in final form* 2*nd November*, 1934.)

SUMMARY.

A theoretical discussion of the electromagnetic properties of aluminium-steel cored cables is given, in which the general cases of a solid and a stranded cable are discussed and the argument is extended to the more complicated case of a composite cable with a magnetic core, showing how the axial flux set up in the core by the spiralling of the outer layers will cause an increase in a.c. resistance and inductance depending on the magnetic properties of the iron and on the arrangement of the strands in the cable.

For the special case when, owing to the spiralling of the two outer layers being in opposite directions, the flux in the core becomes negligible, the inductance may be calculated from the dimensions of the cable and the a.c. resistance from the conductivities of the components.

The experimental work in verification and extension of the theoretical analysis consisted of the measurement of the d.c. and a.c. resistance and inductance, at commercial frequencies, of a short length of transmission line, short-circuited at the end over a wide range of currents by means of the Gall–Tinsley alternating-current potentiometer.

This instrument was made the basis of an arrangement designed to make such measurements a matter of routine, while attaining an accuracy of the order ± ¼ per cent.

Further tests were made to determine the flux existing in the steel core by measuring the voltage induced in a search coil.

The results are discussed in the light of the theoretical analysis and of American practice, and definite figures are established for the British Standard conductors.

INTRODUCTION.

Any solution of the electrical problems of a transmission line depends on a knowledge of the resistance and reactance of the conductor. The constants for all-copper or all-aluminium conductors may be accurately calculated from well-known formulæ, but the presence of a steel core in a steel-reinforced aluminium or copper cable affects these values, so that these formulæ are no longer exactly applicable.

When this work was begun there were no British Standard figures based upon experimental work, but as a result of tests made by Prof. Work† at the Carnegie Institute of Technology, Pittsburgh, for the Aluminium Company of America, the 60-cycle resistance and reactance of the Company's standard conductors have been tabulated and the 25- and 50-cycle figures have been deduced.

The British Standard cables are not the same as the American, and the only available figures are those given by the British Aluminium Co. and B.S.S. No. 215—1925. These give the calculated d.c. resistance of steel-reinforced aluminium cable to four significant figures, neglecting the conductivity of the steel core, which is obviously of the order of 1 or more per cent. It was therefore decided to measure the electrical constants of a small transmission line with as great an accuracy as possible, and so deduce from these laboratory tests figures for the resistance and inductance of the conductor under commercial conditions and for varying frequencies.

The conductors considered in the paper both have a steel core of seven strands of 11-in. diameter wire, one having one layer of aluminium wire (12 strands), and the other two layers (12 and 18 strands). These are referred to as the single-layer and double-layer conductors respectively.

THE ELECTRICAL AND MAGNETIC PROPERTIES OF A COMPOSITE CABLE.

(*a*) *Direct-Current Resistance.*

The direct-current resistance of a composite conductor can be calculated from a knowledge of the specific resistances of the components and the sizes of the cable, by treating the cable as two sections in parallel. This assumes that there is good electrical contact between the layers at the ends of the conductors. In certain types of conductors the steel core is covered with bitumen, so that there is no contact between the steel and the aluminium, and unless the end clamp makes definite contact with the core the conductivity of the steel may be neglected.

In calculating the resistance of any stranded conductor, allowance must be made for the fact that the current will follow the actual strands owing to the relatively large contact resistance between them. This results in an increase in resistance, usually amounting to 2 per cent for the particular "lay" used in British practice.

(*b*) *Alternating-Current Resistance.*

The alternating-current resistance may differ from the resistance on direct current, for the following reasons:—

(1) Skin and proximity effects will increase the resistance of the conductor. (These effects have been shown† to be negligible on the sizes under consideration at 50 cycles per sec.)

(2) A redistribution of current may take place between the strands of the conductor owing to their different

* Part of a thesis approved for the Degree of Master of Science (Engineering) in the University of London.

The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of the Institution not later than one month after publication of the paper to which they relate.

† W. NESBIT: "Electrical Characteristics of Transmission Circuits."

† NESBIT: *loc. cit.*

impedances on alternating current. (This effect will occur on any stranded conductor, and may be assumed negligible at commercial frequencies.*)

(3) There will be a small increase in resistance of the steel core on alternating current.† (As the steel will only carry a small fraction of the total current—of the order of 5 per cent—the final correction will be small, and will not generally exceed 1 per cent.)

(4) The spiralling of the strands produces a longitudinal flux in the steel core which may be sufficient to cause an appreciable iron loss, possibly amounting to 20 per cent of the total loss in the case of a single-layer type of conductor. In a 2-layer conductor the "lay" is in opposite directions, so that the ampere-turns of the two layers are in opposition and only a small flux exists in the core.

(c) *Inductance.*

In this section an attempt is made to calculate the property under discussion with an accuracy of the same order as that obtained in the actual measurements, namely 0·2 per cent.

(i) *Stranded conductor.*—A calculation of the inductance of a stranded conductor has been made by Dwight,‡ who has given results for standard conductors. As a result of this analysis it is shown that the effect of stranding may be accounted for by a correction to the constant term. In that calculation the following assumptions are made.

(1) That the conductor is so long that the spacing and radius are small in comparison.

(2) That each strand carries the same proportion of the total current. (This is not exactly true, as each strand may be regarded as being insulated from the others, and, as each will have a different reactance due to its particular position, the current will distribute itself so as to give the same voltage-drop per unit length.)

(3) That it is permissible to equate the sum of voltage-drops in each of the strands divided by the number of conductors to $2\pi fLI$, where L is the inductance of the whole conductor and I the total current, the voltage-drop in each strand being determined from its self-inductance and the mutual inductance of the other strands, assuming the total current to be equally divided between the strands. (This is, of course, an inaccurate view, since the voltage-drop per ft. must be the same in all the strands and the currents in each of the strands will be different. It would be possible to make an accurate calculation by equating the voltage-drops and calculating the current in each strand, but this would involve an impracticably long calculation.)

(ii) *Composite Cable.*—The general problem has again been discussed by Dwight,§ but an attempt is made here to calculate the correction. The simple case of a solid rod surrounded by an aluminium tube will be considered, and it will be assumed that the current density in each component of the circuit is uniform, neglecting skin effect and eddy currents.

By determining the total energy stored in the magnetic field due to the current in the steel and aluminium portions of the conductor, and equating this value to $\frac{1}{2}LI^2$, where L is the inductance of the circuit and I the total current in the conductor, it can be shown that the inductance of the composite conductor per cm is

$$\log_\epsilon \frac{d}{r_e} + \frac{1}{[r_e^2-(1-k)r_1^2]^2}\left[\frac{r_e^4-r_1^4}{4} - r_1^2(1-k)(r_e^2-r_1^2) + r_1^4(1-k)\log_\epsilon \frac{r_e}{r_1} + \frac{kr_1^4}{4}\right]$$

where d is the distance between the centres of the two parallel conductors, r_1 is the radius of the steel conductor, r_e is the external radius of the conductor, and k is the ratio of current density in the steel to that in the aluminium. When k is small this value approximates to the inductance of the aluminium portion of the conductor alone, and for practical purposes is sufficiently accurate.

Thus it is only necessary in calculating the inductance of a stranded tubular cable to consider the aluminium portion, when Dwight's method may be used, as expressed in the usual form $2\log_\epsilon \frac{d}{r_e} + k$. For the 2-layer cable having 30 strands of aluminium, it was found by calculation that k was 0·38; for the single layer of 12 strands k was 0·36.

The inductance will be increased by the effect of longitudinal flux produced by the spiralling of the strands, but it will only be possible to determine the correction by experiment. The effect of the redistribution of current due to skin effect will be negligible at 50 cycles per sec. for the size of conductor used.

Thus a correction to the constant term in the standard formula may be expected as calculated above, and a further correction due to the spiralling of the strands may be determined by experiment.

Method of Test, and Arrangement of Apparatus.

The conductor under test was arranged as a short-circuited transmission line about 100 ft. long, supported at frequent intervals and held under sufficient tension to avoid appreciable sag, by non-magnetic clamps, provision being made to supply the conductor with alternating current up to 600 amperes or direct current up to 100 amperes.

After due consideration it was decided to use the Gall–Tinsley co-ordinate alternating-current potentiometer to measure the vector voltage and current of the transmission line under test, in view of its flexibility with regard to frequency and range of current and its capability of considerable accuracy. The theory of the co-ordinate a.c. potentiometer has been dealt with in various places. It consists essentially of balancing the unknown potential difference against the sum of two known variable potential differences in quadrature. The current in one slide wire is set to a standard value by a dynamometer ammeter (calibrated on direct current), while a mutual inductance whose primary is in series with the other or "quadrature" slide wire provides a link between the two standard voltages; the secondary voltage of the latter is balanced against a standard setting on the first or "in phase" slide wire, the value of

* Nesbit: *loc. cit.*
† E. C. Walton: *Journal I.E.E.*, 1928, vol. 66, p. 1065.
‡ "Transmission Line Formulas," chap. 8.
§ *Ibid.*, chap. 20.

the inductance being chosen so that in this condition currents of the same magnitude are flowing in the two potentiometers.

In some cases it is not possible to supply two currents in quadrature, but it can be shown that if they are nearly in quadrature their phase difference may be determined by balancing the secondary e.m.f. of the standard mutual inductance against the two potentiometers by assuming in the first place that the two currents are exactly in quadrature. This will be a first approximation, and if necessary the process may be repeated to determine more exactly the angle between the potentiometer currents or the co-ordinates. The co-ordinates having been found, it is a simple matter to determine exactly any e.m.f. measured on them.

The 2-phase supply to the potentiometer was provided through two step-down transformers from a 2-phase alternator, coupled to a battery-driven motor, whose speed was checked by a stroboscopic disc illuminated by a neon lamp, fed from a tuning-fork-controlled valve oscillator. One phase was used to supply the transmission line, and it was found that by careful attention to all moving contacts it was possible to keep the voltage variation to within $\frac{1}{3}$ per cent. A Schering-type vibration galvanometer (screened by a large iron bell-jar from stray fields) was used, a particular advantage being its insensitivity to harmonics.

The currents were measured by standard shunts, and the voltage was determined either directly or through potential dividers, the leads to the instruments being twinned to avoid inductive effects. The conductor was allowed to attain an even temperature before test, this being checked by thermocouples.

The errors likely to arise in the use of the a.c. potentiometer are well known, and it may be accepted that the apparatus is capable of the accuracy claimed, given a suitably steady supply.

The voltage and current waves were very nearly sinusoidal, but as the a.c. potentiometer only measures the value of the fundamental this is not of importance. The dynamometer ammeter reads the r.m.s. value of the potentiometer current, so that small harmonic content will have a considerably reduced effect on the ammeter reading.

Data and Test Results.

A preliminary test was carried out on a copper conductor whose a.c. resistance could be rigidly calculated at 50 cycles per sec. from the d.c. figures, to determine whether any stray losses were occurring. A series of tests were also made to determine the limits of the errors of observation; these were shown to be within $\pm 0 \cdot 25$ per cent. A test, made on direct current, to determine whether any contact effects were occurring due to the direction of the current, gave negative results.

(*a*) *Double-Layer Conductor*, 30/·11-in. *aluminium*+7/·11-*in. steel.*

The resistance per 1 000 ft. of this conductor at 18° C. on direct current was 0·0466 ohm, and the resistance per 1 000 ft. at 18° C. on 50-cycle alternating current was 0·0466 ohm. The figure for alternating current was the same on 25, 50, and 100 cycles per sec. It was independent of current up to 200 amperes, and of the spacing of the conductors.

The inductance was measured on three spacings—6 in., 1 ft., and 2 ft.—and for any one spacing was independent of frequency and current density. From these three sets of tests the value of the constant in the standard formula was deduced, giving a mean value of 0·47. Hence the inductance per cm of double length of conductor is $2\left(2 \log_\epsilon \frac{d}{r_e} + 0 \cdot 47\right)$.

(*b*) *Single-Layer Conductor*, 12/·110-*in. aluminium* + 7/·110-*in. steel.*

The experimental results were as follows:—

Frequency	Current	Resistance per 1 000 ft. at 20° C.	Inductance constant
cycles per sec.	amperes	ohm	k
D.C.	—	0·1180	—
50	25	0·1190	1·75
50	50	0·1195	1·95
50	75	0·1120	2·05
50	100	0·1125	2·15

The inductance is expressed in the form:—
Inductance per cm of double length of single-layer conductor

$$= 2\left(2 \log_\epsilon \frac{d}{r_e} + k\right)$$

The effect of a standard support and insulator guard-ring was to increase the resistance of 1 000 ft. of the conductor by 0·0001 ohm and its reactance by 0·0001 ohm at 50 cycles per sec.

Conclusions.

The results of tests on the 2-layer type of conductor show that for practical purposes the d.c. resistance, and the inductance calculated from the standard formula for a solid conductor of the same external diameter, may be used.

Reasonable agreement was obtained between the calculated and measured values, but the theoretical discussion shows that it is necessary to base calculations on the actual test figures.

Larger divergencies from the d.c. resistance and the inductance calculated from standard formulæ are obtained, as expected, for the conductor having a single layer of aluminium; but, again, for practical purposes these theoretical values may be used. The corrections are given in the paper.

From the tests made it was possible to form an opinion as to the advantages of this type of a.c. potentiometer and to compare the potentiometer method with the wattmeter method for impedance measurement.

The co-ordinate potentiometer has the advantage over the Drysdale type that the phase-shifting transformer (whose calibration depends on the input voltages being balanced and whose scale cannot be read more accurately

than to, say, $\frac{1}{2}$ degree) is avoided and is replaced by a mutual inductance, a much simpler piece of apparatus. As the calibration of the potentiometer is effected by measuring the open-circuit voltage of the mutual inductance, it is directly dependent on the frequency, which must be known to within the limits allowed for test; whereas a wider variation may be permitted with the Drysdale type. This makes the latter type more suitable for a works laboratory. The use of the dynamometer for referring the calibration to the standard cell has been criticized, but some such artifice is necessary for any a.c. potentiometer, and as alternating-current measurements are rarely possible within closer limits than $\pm 0 \cdot 1$ per cent the error involved is negligible. It may therefore be said that for accurate work the co-ordinate potentiometer is better, while for routine testing the Drysdale–Tinsley potentiometer is more convenient, cheaper, slightly easier to operate, and does not require the supply frequency to be accurately known.

The advantages of the potentiometer for impedance measurements over the wattmeter method are chiefly: (1) It involves no standards other than one resistance and potential divider. (2) Its range may be conveniently extended by the use of current and potential transformers. (3) It may be used at low power factors and low powers without introducing any unknown errors. Against this are to be stated the disadvantages of increased cost and initial experiments in setting up the apparatus and slightly more involved operation, but in the laboratory fitted with an a.c. potentiometer this instrument would be used without question for impedance measurements, as described in this paper. Current transformers may be constructed employing mumetal, and calibrated by the use of only two standard resistances on the potentiometer, thus saving reference to outside apparatus.

The work described in this paper was carried out at University College, London, under the direction of the late Prof. W. C. Clinton.

THE ORGANIZATION OF ELECTRICITY SUPPLY IN NEW ZEALAND.

By F. T. M. Kissel, B.Sc., Member.

(*Paper first received* 15*th November*, 1933, *and in final form* 18*th April*, 1934; *read before* The Institution 20*th December*, 1934, *before the* North-Western Centre 6*th November*, 1934, *and before the* Western Centre 18*th February*, 1935.)

Summary.

A précis is given of the principal Acts dealing with electricity supply and the use of water power; in particular, the Electric Power Boards Act, which has been the authority under which much of the rural reticulation has been carried out, is reviewed. An analysis is given of the various types of authorities controlling the supply.

Maps illustrate the extent to which the country has been reticulated, and the location and size of the principal generating stations are indicated.

The capital expenditure involved reaches over 32 million £. Graphs allocate the cost between the Government and the various supply authorities and show how the system has resulted in decreasing costs per unit sold.

The average annual consumption per consumer for all purposes is 1 970 units, and the average price is 1·28d., whilst for ordinary domestic purposes the consumption is 1 067 units per annum and the average price 1·143d.

The figures given are averages compiled from statistics for the year ended 31st March, 1933.

Law Relating to Water Power and Electrical Energy.

The earliest reference to any control of the electric supply business is probably contained in the Electric Telegraph Act of 1865, which, with its amendments, was consolidated in 1875 and was carried forward into "The Electric Line Act" in 1884. This made provisions and conditions relating to the erection of electric lines, both for telegraph and for electric lighting purposes. An "Electric Motive Power Act" (1896) gave power to the Government to make investigation into the possibility of utilizing the waterways of the Dominion for the purpose of supplying electricity to the gold-mining industry, which was an important one in those days. Special Acts, of local importance only, passed between 1890 and 1904 gave powers to various local authorities and companies to erect and operate electric power plants.

The basis of the present extensive development was probably established when the Government passed the "Water Power Act, 1903," which reserved to His Majesty, subject to rights lawfully held, the sole right to use water in lakes, falls, rivers, or streams, for the purpose of generating or storing electricity or other power. It also gave to His Majesty the right to grant to any person or company the right to use water from any fall, river, or stream, to generate electricity for lighting his own premises but not for sale to any other person. It also authorized the granting to any person or company of the right to use water for any agricultural, industrial, or manufacturing purpose other than the generation or storage of electricity. This Act was amplified by the Public Works Amendment Act of 1908, which gave the Crown the right to grant to any person or corporate body licences to use water for the purpose of generating electricity, subject to such conditions as might be imposed. The principal provisions relating to powers to use water for generating electricity and to erect electric lines have been consolidated in Part XIII of the Public Works Act, 1928. This contains the following provisions:—

(*a*) Certain special powers which the Minister of Public Works as representative of the Government may be authorized to exercise in order to utilize water power and to sell electricity generated therefrom.

(*b*) Conditions under which licences may be issued to local authorities and others to use water power and to sell electricity.

(*c*) Authority for the Governor-General to make regulations governing the use and management of any work or lines used for generating or conveying electricity.

Subject to the general provisions of this Public Works Act, more specific powers are given to municipalities by the Municipal Corporations Act, 1920, and to Electric Power Boards by the Electric Power Boards Act (consolidated 1925) and Amendments.

The Municipal Corporations Act, 1920, Part XXVI, gives to municipalities the right to establish electric light works and to supply electricity to consumers within the borough, to individuals living outside the borough if the consent of the local authority of the district in which such person resides is obtained, and to any adjoining local authority.

It does not, however, allow a municipality to supply power to any local authority other than one such as has a boundary in common with it. In the classification of supply authorities given later, the various boroughs which are listed as operating independently of Power Boards are operating under the provisions of the Municipal Corporations Act, and of local empowering acts, and of licences issued under provisions of the Public Works Act.

The Electric Power Boards Act, consolidated in 1925 and since amended in 1927 and 1928, has, however, been the authority under which the greater part of the recent development has been carried out. It is designed to provide for the distribution of electricity in a much more comprehensive way than was possible under the Municipal Corporations Act and other Acts previously dealing with the matter.

Being set up for the specific purpose of operating an electric supply business, a Power Board has no means of diverting any profits made in that business into other avenues, as is possible where the electric supply is operated by municipalities or other local authorities who have other interests which may not be so profitable. Profit over and above what is necessary to establish legitimate reserves must be returned to the consumer

by way of reductions. This is particularly important in the Government's general scheme of electricity supply. This, from its comprehensive nature, must of necessity be highly capitalized in the earlier stages, and as annual charges are largely independent of the load a reduction in the cost per unit supplied must come very largely from the increased consumption of units. Whilst it is not suggested that a reduction in the selling price will be immediately followed by an increase in consumption, there is no question that a reduction in selling price gradually results in an increase in consumption.

The general provisions of the Act are as follows:—

An Electric Power Board district when constituted may consist of areas administered for purposes other than electricity supply by one or more local authorities, which may be borough councils, county councils, or Town Boards. It is generally considered advisable that the district areas should include both rural and urban districts. The area is first constituted following the presentation of a petition to the Governor-General, signed by at least 25 per cent of the ratepayers within the proposed district. The total area allotted to any one Power Board is usually divided into two parts, called the District and the Outer Area. The former is the more closely settled portion and the portion in which by far the greater part of the new reticulation has to be built. It may include both urban and rural districts. The "outer area" is, as might be inferred from the words, generally the more sparsely settled area adjoining the Power Board district. These outer areas have no representation on the Board and are not liable for any of the rates mentioned later. The Board is, however, conditional on obtaining the necessary licence so to do, entitled to erect electric lines within such outer areas. As loan moneys raised on the security of the original rating area cannot be expended in the outer area it is of course not very likely, especially in the early stages, that lines having to be paid for out of revenue will be so erected. Though, generally speaking, the outer area is as described above, there are several cases where boroughs within the general area of supply have already possessed electrical systems of their own but desire to take advantage of cheaper supply by purchasing power in bulk from the Board to serve their own reticulation. Such boroughs, in some cases, prefer to remain in the outer area and retain control of their own system, obviating any possibility of becoming liable for rates in the Power Board district.

If the petition so requires, provision may be made for the Board to be elected by the District as a whole, but otherwise representation of the various parts of the district on the Board is based on the valuation and population, and election is on the same franchise as is usual for the ordinary local-body elections in different parts of the District. With the exception of the Chairman, who may draw an honorarium not in excess of £300 per annum, members are not paid for their services, but are allowed the reasonable expenses of travelling to meetings. For the year 1933, the total cost representing honoraria and members' travelling expenses, etc., amounted to £11 000.

The Board is given fairly wide powers in regard to finance. It is authorized to borrow, subject to conditions which may be imposed by the Local Government Loans Board and the Local Bodies Loans Act, 1926, moneys which may be necessary to carry out its programme of electrical works.

To provide security for the borrowed capital and to provide against the possibility of losses on operation, particularly in the earlier years of operation, the Board is given various rating powers. Any proposal to raise a loan for capital purposes must be approved by a poll of ratepayers within the area pledged as security, and must be carried by 60 per cent of the voters.

A. The Board has power to strike and levy a uniform special rate over all rateable property in the Board's district, or in such part of it as is specified in the loan proposal, as security for interest and sinking fund on the loan.

B. In order to make up any deficiency in the estimated revenue and expenditure for the year, the Board may either—

(1) Strike and levy a uniform rate over all rateable property in the district sufficient to make good part or the whole of such deficiency or

(2) If part only of such excess is so raised the balance may be raised by a separate rate or by separate rates on such portions as may be defined by Special Order for that purpose.

(3) Before striking a uniform rate under (1) above—A Board may by Special Order determine that payment of the full amount of such rate may be limited to properties to which electricity is available, or which are within 10 chains of the Board's distribution lines.

(4) A Board may from time to time strike a separate rate within any defined portion or portions of its district. This cannot be made to apply to any area in which the local authority or individual is already the holder of a licence to distribute or generate electricity on its own behalf. This rate can also be made to apply only to such properties as are supplied by the Board or are within 10 chains of its lines, and any person liable to pay a rate under this section is also entitled to receive free of charge for use in his property, electricity equivalent in value to the amount of such rate paid in that year.

The Board also has authority to forgo collection of rates under this section if it is satisfied that the owner of the property is unable to take advantage of the supply of electricity with reasonable benefit to himself.

Except for the purpose of securing loans, the rating provisions of the Act have not been used to any considerable extent by Power Boards. In no case has it been necessary to utilize the powers under Section A above, that is, to collect the rate pledged as security for the loan.

Rates to the value of £575 968 have been collected under (1), (2), and (3) of Section B, £457 707 of this amount by one Board. £49 997 has been collected under Section B (4), generally known as the "availability rate." This particular method of rating has been used in one or two cases as a means of forcing ratepayers to become consumers of electricity, and its value for this purpose falls away as ratepayers within the reticulated area become consumers.

Of the total of £625 966 that has so far been collected in rates, £552 144 has been collected by Power Boards which are operating independently of the Government supply, and £73 822 by Boards deriving power in bulk from the Government.

As reticulation systems such as those constructed must be designed to provide not only for present needs but also to a considerable extent for future requirements, they should not be expected to earn invariably sufficient revenue in earlier years to meet all expenses of operation and capital charges. This is, of course, usual in any initially highly-capitalized business, and provision has been made to allow Boards to capitalize interest charges during construction and to carry forward losses over a period of years to be repaid out of future profits.

To enable this to be done, Boards are authorized by Section 70 of the Act to borrow by way of overdraft, but the amount owing under this authority must not exceed a certain proportion of the capital expenditure. This proportion is 3 per cent at the end of the first year, but increases by steps to 7 per cent by the end of the fourth year; thereafter it must be gradually reduced and the amount must be completely repaid by the end of the eighth year.

Subject to the conditions of the Public Works Act, mentioned earlier, and to a certain amount of Government supervision, the Power Boards are authorized to erect generating works and transmission systems, purchase or sell electricity, enter into contracts with public authorities or individuals for the supply of power, and generally to do practically all things necessary for, or incidental to, the business of supplying electricity.

The Governor-General is empowered at any time, upon giving 12 months' notice, to purchase the works of a Power Board at a price to be settled by arbitration. This power has not yet been exercised.

The actual location of the various Power Board areas is shown by the areas enclosed within dotted lines in Figs. 1 and 2.

Where supply is taken from one of the main Government schemes the area allotted to any one Power Board is usually such that it can be economically reticulated from one main substation or point of supply, and may be 700 to 800 square miles in extent. Areas of similar size are usual also where supply is from a power plant owned by some local authority. When the movement for this system of control first began, maps were prepared dividing the whole Dominion into 55 such areas. In the main, this subdivision has been adhered to, though local and other interests have necessitated departures from it in some cases. Altogether, 45 of the originally proposed Boards have been actually constituted and 40 of them are functioning as supply authorities.

Power Boards' Association.

Since 1920, the various Power Boards have joined into an Association which holds annual meetings to discuss problems in which they are interested, and to bring before the Government proposals for amendment of laws or regulations which they consider might be to their advantage. At first, this Association was limited to members of Power Boards, but it has since been extended to include members of other types of supply authorities. In 1930 the "Electric Power Boards and Supply Authorities Association Act" gave the Association legal status as a corporate body.

Local Government Loans Board Act.

Legislation in 1926 constituted a Board known as the Local Government Loans Board, whose special function it is to control the borrowings of local authorities. The consent of this Board has now to be obtained before any loan is submitted to the ratepayers. Before authorizing the loan the Board obtains reports from competent authorities on the necessity for the loan, the suitability of the works proposed, the extent to which other means of supplying the need are available, the financial prospects, and any other relevant considerations. In practically no case now are lines being built or extended into areas unless sufficient revenue is in sight to provide a reasonable return on the investment. In many cases the Loans Board is insisting on a guaranteed revenue equal to 17 per cent of the capital cost being available before authorizing loans for extension purposes.

Registration of Electrical Wiremen.

The comparatively rapid growth of electrical development in the past 10 years has necessitated the employment of an increased number of men on electrical installation work, and as there is considerable variation in the qualifications of the workmen there has been corresponding variation in the quality of the work performed. In industry of any magnitude, the operations of men engaged on installation work could probably be quite well looked after by skilled staff, but in ordinary house wiring in particular the owner or ordinary small building contractor might be quite incompetent to judge whether the work for which he was paying was being carried out in a skilled and proper manner. For some time certain of the individual supply authorities in the Dominion had had systems of registration of electrical workers in their own areas, but with work going on in so many places there were indications that men who had been found guilty of bad workmanship in one locality moved off to another and there carried on similar practices.

To meet this difficulty, and to provide generally for raising the standard of wiring work, the "Electrical Wiremen's Registration Act" was passed by Parliament in 1925, and came into operation on the 1st April, 1926.

The Act is administered by a Board of five members called the "Wiremen's Registration Board." The Chief Electrical Engineer of the Public Works Department is Chairman and is assisted by four other members appointed for periods of three years and nominated by the electrical supply authorities, the electrical contractors, the Council of the Fire Underwriters' Association, and the Electrical Workers' Union, respectively.

Since the Act came into operation 3 300 men have been registered as electrical wiremen, and 405 as inspectors of electrical wiring. Limited registration has been granted in 330 cases.

The cost of administration is met in the main by registration and examination fees, and the balance of about £1 000 to £1 200 per year is met by a levy on electrical supply authorities on a basis *pro rata* to annual revenue.

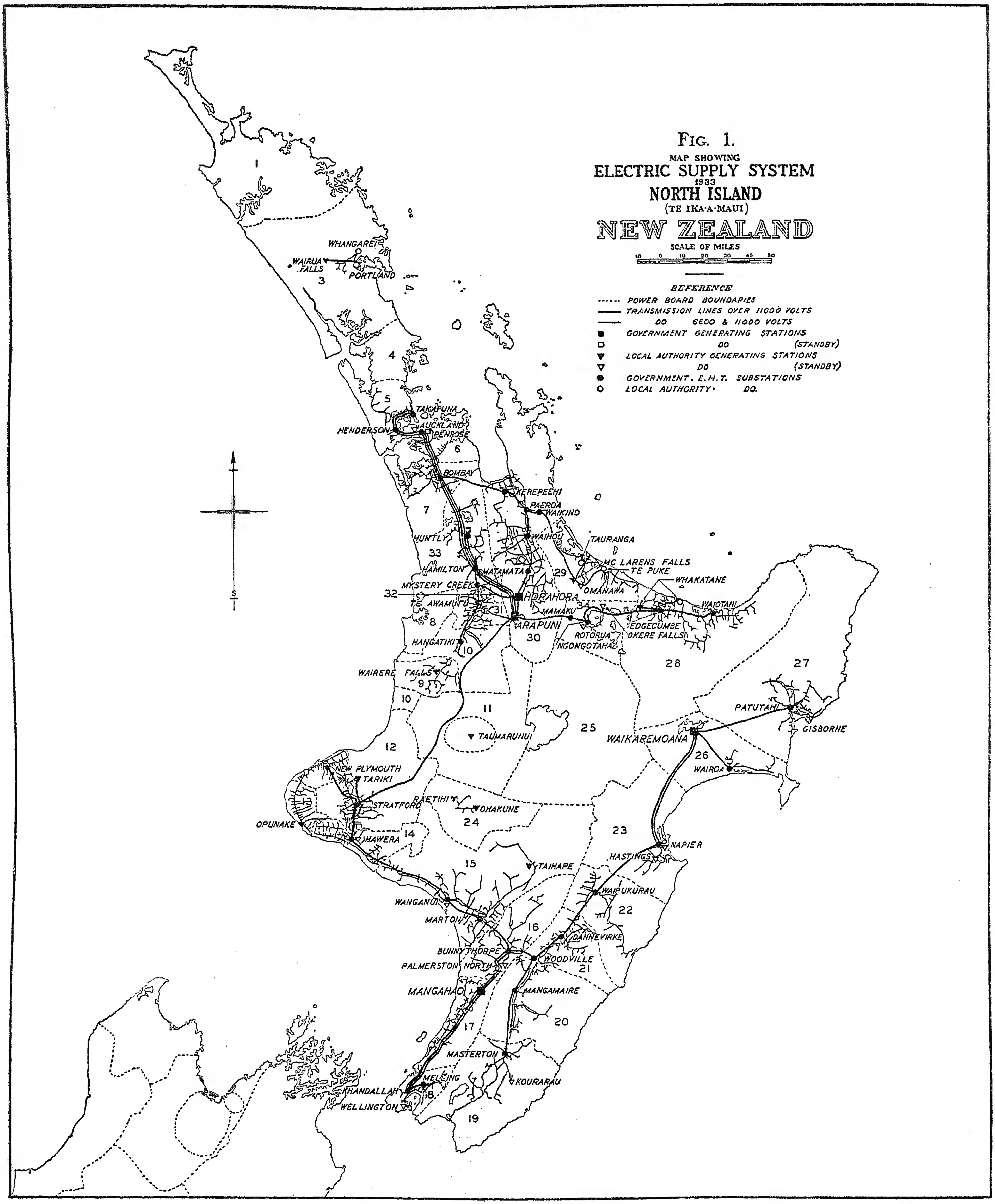
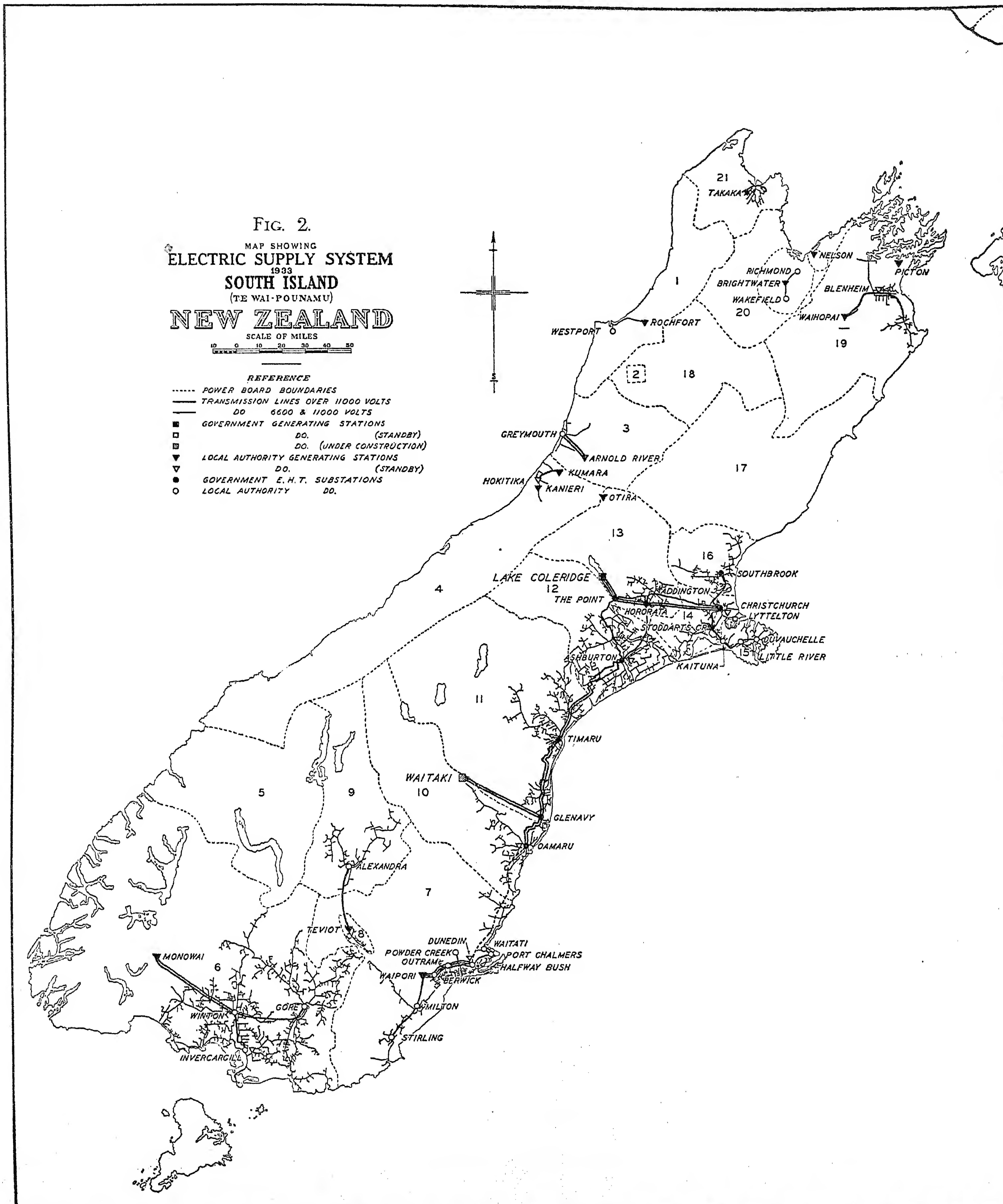


FIG. 1.
MAP SHOWING
ELECTRIC SUPPLY SYSTEM
1933
NORTH ISLAND
(TE IKA-A-MAUI)
NEW ZEALAND

It is, of course, difficult to assess the value derived from registration, but supply authorities generally admit that it has undoubtedly improved the general standard of work done, and there is also no doubt that the number of electrical fires and of electrical accidents has not increased in anything like the degree to which the number of installations and consequent risks of fire or accident have increased.



Regulations.

As mentioned earlier, the Public Works Act, 1928, gives to the Governor-General the right to make regulations governing the use and management of electric lines and works. The executive Government Department for this purpose is the Public Works Department, which thus acts in a somewhat dual capacity. It is, itself, the largest supply authority in the Dominion, and, as such, is subject to the same regulations as govern other authorities. In another capacity it is also required to exercise regulatory

control over all other supply authorities and over electrical works generally.

The actual regulations are drawn up for submission to the Executive Council of the Government by an Honorary Committee representative of various electrical interests. The author, as Chief Electrical Engineer of the Public Works Department, is Chairman, and there are also one other member and the Secretary representing that Department, two members representing the electric supply authorities, one each representing the Post and Telegraph Department and the Railways Department, the principal Government Departments other than Public Works which are interested in electricity supply, and one each representing the electrical traders and the electrical workers.

All regulations for wiring are generally based on the regulations issued from time to time by the Institution of Electrical Engineers, modified and amplified where necessary to suit New Zealand conditions. Inspection in general is carried out by inspectors appointed by the supply authorities in conformity with the Wiremen's Registration Act. In addition, the Public Works Department of the Government has a small inspection staff whose main function is to carry out periodic inspections of the electric lines and plant belonging to the various supply authorities, and to make occasional inspections of household wiring work in different areas to see that the detailed work of wiring inspection is being carried out in a reasonably uniform manner in all parts of the Dominion.

Controlling Authorities.

Although purchase of power in bulk from the Government and reticulation by Power Boards in both urban and rural districts, as described earlier, may be regarded as the standard system, it is by no means the only one. Supply authorities might be classified into seven groups, each representing a different system of control, as shown in Table 1.

Class "A" in the Table represents what might be called the "standard system" of power generated by the Government and supplied to the actual consumers by a Power Board.

Class "B" departs from Class "A" only in that in some cases the Power Board sells part of its supply to existing local authorities for distribution to the actual consumers.

Classes "C" and "D" correspond to Classes "A" and "B" except that the generating works in these classes are not owned by the Government.

Class "E" includes authorities other than Government Departments or Power Boards, which, to some extent, exercise the functions of Power Boards in supplying electricity in special licensed areas outside the area controlled for ordinary municipal (or business) purposes. They differ essentially from Power Boards in that the outside areas have no representation in the control of the undertaking, and in that they have no power to levy rates outside their own municipal boundaries. The Class includes eight authorities, all of which, with the exception of Christchurch, generate their own power. Christchurch purchases power from the Government. In addition, Dunedin City has contracted to take, and New Plymouth Borough now takes, part of its supply from the Government system.

Class "F" represents eleven supply authorities in which it could be claimed that the Government itself has departed from the principle of Power Board legislation by giving supply direct to authorities other than a Power Board. Of the eleven authorities listed, seven are in the Christchurch area, where Government supply was available before the Power Board legislation was in existence. Though the Power Board movement is extending slowly in Canterbury, it has not been found possible, so far, to persuade any of these seven authorities to join up into Power Board areas.

Of the others, Dunedin and New Plymouth, which are also in Class "E," take or have contracted to take a portion only of supply from the Government so as to obviate duplication of capital expenditure on additional generating works.

Wellington, although its activities are confined to the ordinary municipal area, has never been included in any Power Board area, as it is somewhat cut off physically from the adjoining Hutt Valley, which, in any case, is sufficiently large to function quite efficiently as a separate Power Board area.

The remaining Borough of Hamilton was omitted from the Central Waikato Power Board to which it might have been joined, when the Waikato Boards were being set up in the early days of Power Board legislation.

Extent of Development.

The two maps, of the North and South Islands respectively (Figs. 1 and 2), show the main generating plants, and the transmission and distribution lines at voltages from 6 600 volts upwards, and give a general view of the extent to which supply has been made available throughout the Dominion.

As lines at lower voltage than those shown will not radiate very far from these lines, the areas enclosed by joining up their extremities give a very close representation of the total area of the country that has been reticulated and in which electricity is being fairly generally utilized.

The first impression gathered from a glance at these maps would probably be that the electrical development scheme has not proceeded very far. There is still a very large proportion of blank space. The total area of the Dominion is about 103 000 square miles, and of this area about 10 250 square miles in the South Island and 10 930 miles in the North Island may be regarded as being within reticulated areas. In other words, electricity is available in about 21 180 square miles, or in slightly over 20 per cent of the total area. Of the 10 930 square miles reticulated in the North Island 10 280 are connected to the Government system, and only 650 are supplied from other authorities' generating plants. In the South Island, on the other hand, the Government system supplies only 4 640 square miles, whilst other authorities supply 5 610 square miles. Contracts have been entered into, however, by which 990 square miles of this area will receive part at least of the supply from the Government.

When, however, the nature of the country in most of these blank white spaces on the maps is considered, the position appears in a totally different light. The blank spaces are very largely mountainous, or areas in which,

TABLE 1.

Class	General description	Power Boards: Number (1)	Power Boards: Population, inclusive of Boroughs and Town Districts scheduled in Col. (4) (2)	Power Boards: Capital investment (exclusive of Government) (3)	Included Boroughs and Town Districts operated by Power Boards: Number (4)	Included Boroughs and Town Districts operated by Power Boards: Population (5)	Boroughs and Town Districts operating own districts: Number (6)	Boroughs and Town Districts operating own districts: Population (7)	Boroughs and Town Districts operating own districts: Capital investment (exclusive of Government) (8)
A	Power Board in control of whole supply and using Government power	19	520 245	£7 505 041	67	326 750	—	—	—
B	Power Board selling Government power in bulk to other supply authorities	9	189 858	£2 836 893	22	57 540	14	92 628	£835 204
C	Similar to " A " but not using Government power	7	44 718	£891 470	17	21 700	—	—	—
D	Similar to " B " but not using Government power	6	93 455	£2 663 894	16	20 660	11	48 940	£581 443
E*	Supply authorities (other than Power Boards) with extended areas of supply	Nil	—	—	—	—	(*a*) 8	229 380	£3 481 044
F*	Supply authorities (other than Power Boards) supplied direct by Government	Nil	—	—	—	—	(*b*) 10	365 210	£4 403 796
G	Isolated authorities	—	—	—	—	—	(*c*) 11	19 358	£204 387

* The electric supply systems at Christchurch, Dunedin, and New Plymouth (population 208 000, capital investment £2 961 100), are included under both " E " and " F."

(*a*) Includes two private companies. (*b*) Includes two county councils. (*c*) Includes three county councils and two private companies.

For further particulars, including names, population, and capital investment in the various Power Board areas, and included borough and town board areas, see Appendix.

for some reason or other, population is sparse. Statistical figures, however, place a very different complexion on the matter. Electric supply is available to about 93 per cent of the total population, and each unit of population within the reticulated area has used, on the average, 452 units of electricity during the year under consideration and ending on the 31st March, 1933.

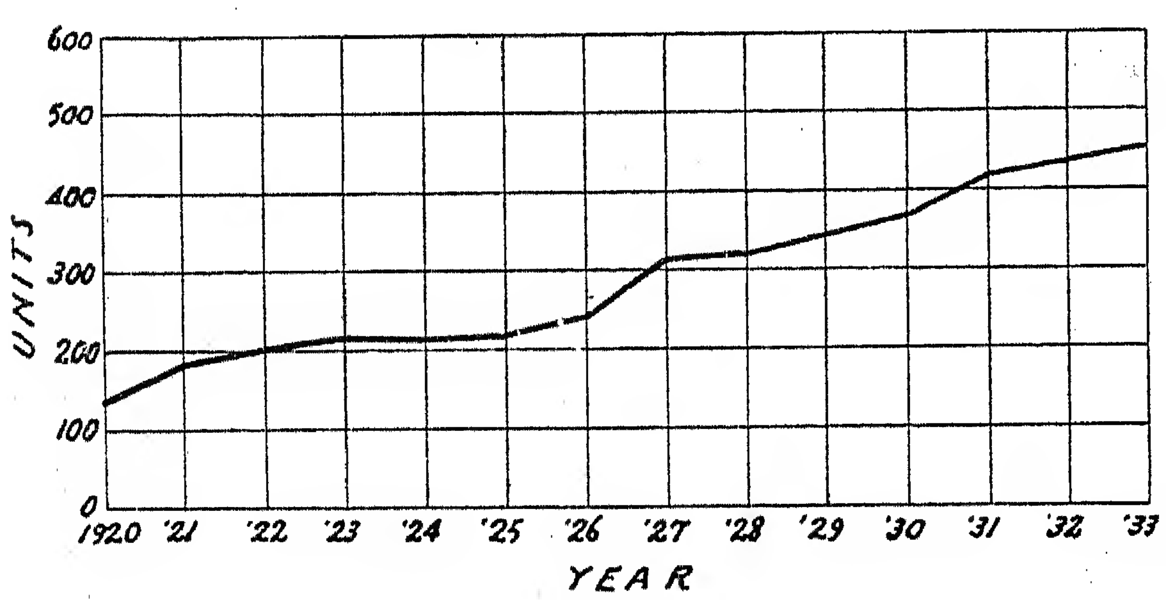


FIG. 3.—Units sold per head, 1920–1933.

Consumption per head.

Fig. 3 shows the way in which the consumption per head within the reticulated area has been increasing since 1920.

THE POWER SUPPLY.

The principal generating stations, transmission lines, and substations, are shown on the maps. For the North Island the principal sources of supply are the Government water-power stations at Mangahao, Arapuni, Horahora, and Waikaremoana. It is not proposed to describe these in any detail. The capacities are as follows:—

Mangahao, on the river of that name, is of 19 200 kW capacity, operates on a head of 875 ft., generates at 11 000 volts, and steps up to 110 000 volts for transmission.

Arapuni, on the Waikato River, has a present capacity of 60 000 kW but is capable of extension to 120 000 kW. It operates on a head of 175 ft., generates at 11 000 volts, and steps up for transmission at 110 000 volts, and is also connected at 50 000 volts with the Horahora station 6 miles away on the same river.

Horahora has a capacity of 10 600 kW, generates at 5 000 volts, and steps up to 50 000 volts for transmission. This station was built originally in about 1913 with a capacity of 6 300 kW by the Waihi Gold Mining Co. for power supply to its mine and battery, which still use about 3 000 kW of the output. It was purchased by the Government in 1919, and its capacity was increased by 4 000 kW shortly afterwards.

Waikaremoana, on the Waikaretaheke River, the outlet of Lake Waikaremoana, has a present capacity of 32 000 kW. This is capable of extension to 120 000 kW, partly in the present station and partly

in two further stations short distances above and below the present one. It generates at 11 000 volts and steps up to 50 000 and to 110 000 volts for transmission.

At present, the 110 000-volt transmission systems radiating from Mangahao and from Waikaremoana are interconnected; a further line at this voltage is nearing completion and will interconnect this system, which serves the southern part of the island, with the Arapuni–Horahora system, which serves the more northern half of the island. This line will probably be completed by the time this paper is published, and it is therefore shown on the map (between Arapuni and the Stratford substation).

Further plans provide for another interconnecting link between Waikaremoana and Arapuni by the direct route via Rotorua. They provide also for an extension of the present 50 000-volt line, which serves the Waitemata Power Board, from the Henderson substation to North Auckland, where it will interconnect with a system at present supplied from a water-power and steam plant belonging to Wilson's (N.Z.) Portland Cement Co.

In the South Island the principal sources of supply are the following water-power stations:—

The Government power station at Lake Coleridge, which first went into operation in 1915, and now has a capacity of 34 500 kW. It generates at 6 600 volts and steps up for transmission to 66 000 volts.

The Waipori power station belongs to the Dunedin City Corporation and has a capacity of 17 000 kW. Generation is at 5 000 volts and the voltage is stepped up to 33 000 for transmission.

The Lake Monowai plant of the Southland Electric Power Board has a capacity of 6 000 kW, generates at 6 600 volts, and steps up for transmission to 66 000 volts.

The New Zealand Government has under construction a further water-power plant on the Waitaki River, where the initial installation will be of 30 000 kW capacity. It will generate at 11 000 volts and step up to 110 000 volts. It will be interconnected at Glenavy with the Lake Coleridge system to the north and with the Dunedin system to the south.

The West Coast, Marlborough, and Nelson areas are supplied by other smaller plants not interconnected in any way with the general system.

Wherever generating plants were in existence prior to the advent of Government power into an area, these plants, if at all economical, have been interconnected with the general system, and have become available for stand-by purposes, peak-load reducing, or such other purpose as the nature of the contract with the owners would permit.

Of the total power generated in the Dominion for the year ended 31st March, 1933, 96·3 per cent (798 417 321 units) was generated in the first 26 plants, which may be considered to represent the basic supply stations. Of the remainder, 3·2 per cent (26 537 572 units) was generated in the plants numbered (27) to (40) mainly for stand-by, peak-reduction, or other special circumstances, whilst the remainder of 0·5 per cent (4 329 878 units) was generated in various other smaller plants in the main supplying more or less isolated communities.

Types of Generating Plant.

Fig. 4 shows the number of public-supply generating plants of various kinds in operation as main sources of supply over the past 13 years. The number of water-power plants has remained fairly constant at about 30. Gas-driven plants were next in favour about 10 years ago,

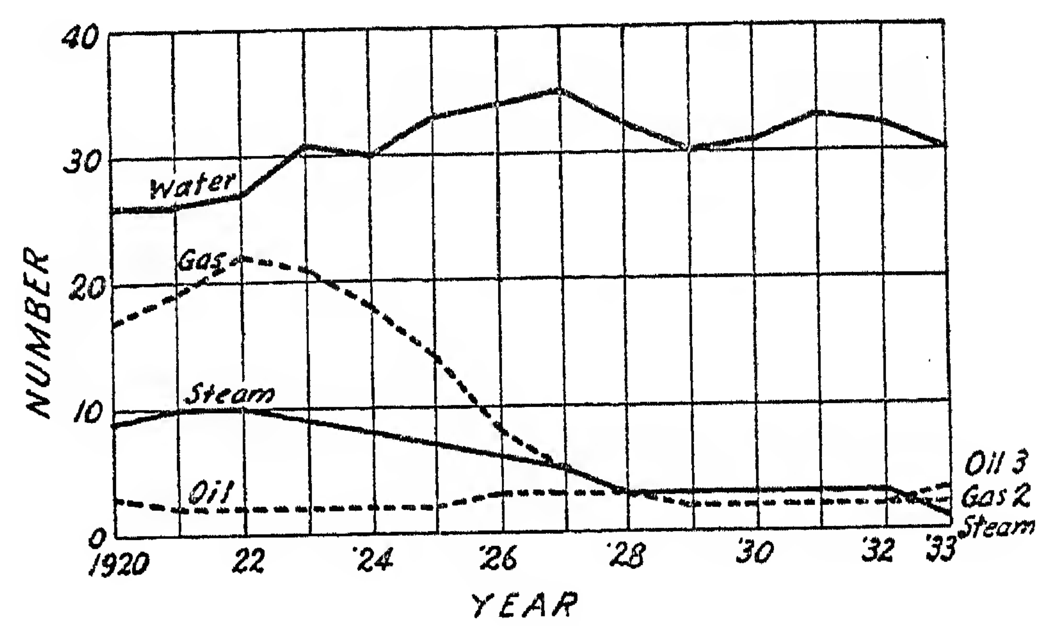


FIG. 4.—Number of public supply power stations, 1920–1933.

but in more recent years the numbers have fallen away from a maximum of 22 in 1922 to only 2 at the present time. So, also, steam plants which reached a maximum of 10 in 1922 have gradually declined in numbers until at present there is only one (in Nelson) which furnishes the main supply. A number, of course, are still maintained for stand-by or emergency purposes. The chief of these are the King's Wharf plant of the Auckland Power Board (41 600 kVA) and the Evans Bay Plant of the Wellington City Council (7 650 kVA).

The number of oil-driven plants has never exceeded 3, but has varied between 2 and 3 over the period.

Sizes of Generating Plants of different types.

Fig. 5 gives some idea of the magnitude of these plants. The water and steam plants are much the larger in size, and the vertical scale of these two on the graph is 50 times greater than for the oil and gas plants.

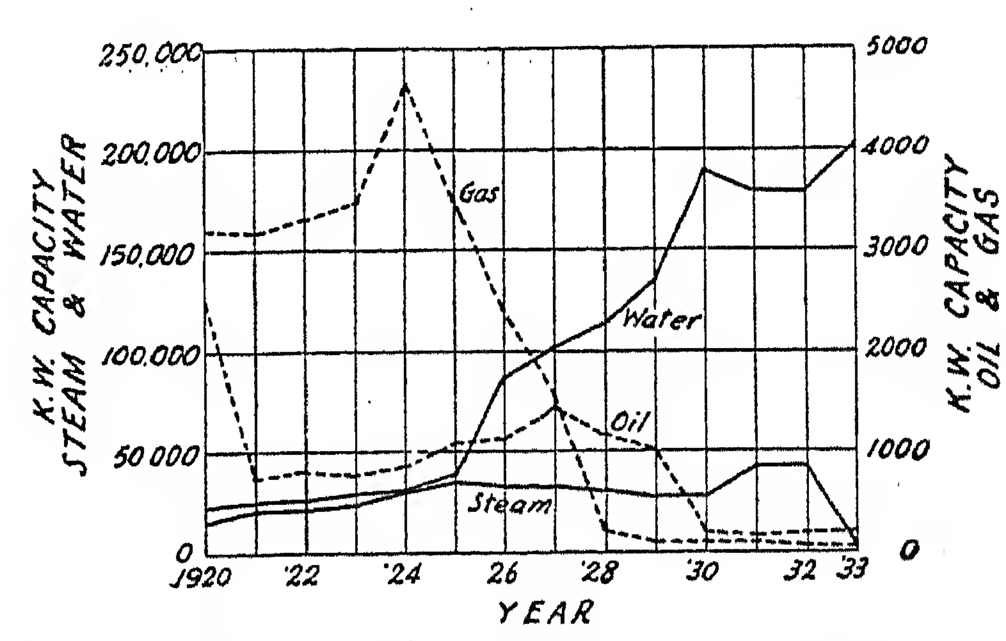


FIG. 5.—Capacity of public supply power stations, 1920–1933.

Extent of Generation by different types.

Of the total units generated during the year (829 284 771), 79·6 per cent (660 361 548) were generated in the Government-owned stations, and a further 1·4 per cent (11 859 315) in stations controlled by the Government but owned and operated by the local authority. Looked at in still another way, 98·4 per cent of the total

units were generated by means of water power and only 1·6 per cent by other means.

As further illustrating the extent to which Government power is becoming the predominating feature in electricity supply, it might be mentioned that of boroughs or town board areas in which electricity is available, Government power is used wholly in 109 cases and partly in 8 cases, and power generated elsewhere, wholly in 54 cases and partly in 8 cases. The boroughs, of course, are practically the only places in which power was available before the advent of Government supply. In rural areas the predominance of Government power would be even more marked.

In the same way as generation by the Government is

TABLE 2.—*Summary of Generating Plants over 250 kVA Capacity.*

Location	Type	Owner	Capacity	Units generated, 1932–33
			kVA	
(1) Arapuni	Water	New Zealand Government	72 000	222 253 140
(2) Horahora	Water	New Zealand Government	12 860	55 111 780
(3) Waikaremoana	Water	New Zealand Government	41 000	199 113 298
(4) Mangahao	Water	New Zealand Government	24 000	40 805 060
(5) Lake Coleridge	Water	New Zealand Government	40 580	119 915 190
(6) Hawera	Water and oil	South Taranaki Power Board	615 605	1 428 480
(7) New Plymouth	Water and oil	Borough Council	4 700 300	12 048 169
(8) Waipori	Water, oil, and steam	Dunedin City	23 125 860 2 340	62 360 570
(9) McLarens Falls (10) Omanawa	Water	Tauranga Borough	3 500 800	11 919 956
(11) Opunake	Water	Opunake Power Board	435	1 562 200
(12) Tariki	Water	Taranaki Power Board	3 600	10 558 200
(13) Taumarunui	Water	Borough Council	500	872 555
(14) Ohakune	Water	Borough Council	261	259 600
(15) Arnold River	Water	Grey Power Board	3 600	6 438 117
(16) Nelson	Steam	City Council	1 561	2 145 040
(17) Raetihi	Water	Borough Council	470	492 430
(18) Wairua Falls	Water	Portland Cement Co.	2 500	8 519 750
(19) Golden Bay	Water	Golden Bay Power Board	250	633 860
(20) Kanieri	Water	Kanieri Elec. Co.	920	4 625 700
(21) Teviot	Water	Teviot Power Board	750	3 905 142
(22) Waihopai	Water and oil	Marlborough Power Board	1 250 570	5 654 750
(23) Wairere Falls	Water	Wairere Power Board	480	1 307 290
(24) Kumara	Water	Westland Power Co.	1 120	1 193 300
(25) Westport	Water	Westport Borough	250	697 844
(26) Lake Monowai	Water	Southland Power Board	7 050	24 595 900
In addition to the above, the following plants are available when required.				
(27) Penrose	Diesel	New Zealand Government	3 900	255 200
(28) Huntly	Steam	New Zealand Government	1 500	462 000
(29) Lyttelton	Diesel	New Zealand Government	6 000	12 891 290
(30) King's Wharf	Steam	Auckland Power Board	41 600	9 554 590
(31) Christchurch	Steam	City Council	400	nil
(32) Okere	Water and oil	Tourist Dept., Rotorua	200 187	403 473
(33) Evans Bay	Steam	Wellington City Council	7 650	101 427
(34) Hastings	Oil	Borough Council	1 175	17 440
(35) Napier	Oil	Borough Council	400	129
(36) Palmerston	Gas	City Council	1 350	467 362
(37) Poverty Bay	Oil	Poverty Bay Power Board	1 500	46 952
(38) Kourarau	Water	Wairarapa Power Board	837	2 304 725
(39) Wanganui	Steam	Wanganui-Rangitikei Power Board	1 650	28 884
(40) Invercargill	Steam	City Council	2 450	4 100

the principal means of supply, so the more or less standard system of distribution by Power Boards is becoming the principal means of distribution; of the 171 boroughs and town districts in which power is available, the whole reticulation is controlled by Power Boards in 122 cases and retained by the ordinary municipal local authority in only 25 cases in Power Board areas, and in 18 cases in other areas.

Charges for Bulk Supply.

Power is sold by the Public Works Department in bulk to supply authorities, generally on a maximum-demand rate. The rate is practically the same, irrespective of distance from the power stations, but varies somewhat with the extent of the load. The more or less standard charge is £2 10s. per kVA of maximum demand per quarter for the first 200 kVA of maximum demand, £2 per kVA per quarter for the next 4 800 kVA, £1 15s. per kVA for the next 15 000 kVA, and £1 6s. 3d. per kVA per quarter for all over 20 000 kVA of maximum demand per quarter. At this price, power is delivered to the supply authority at 11 000 volts, 3-phase, 50 cycles, from one of the Government substations, which are generally located somewhere convenient to the centre of the supply authority's district. In the case of the Auckland Power Board, supply is given at 22 000 volts.

There are some modifications, particularly in places where the supply authority previously possessed a generating plant of its own. The Government has not taken any steps to compel the closing-down of these plants, but has endeavoured to modify the standard supply rate to an extent sufficient to secure practically the whole of the load. On a system where the basic system of charging is on a maximum demand these generating plants sometimes attain a value as a means of peak-reducing which is not altogether in keeping with the value they would have if they were required to carry the whole load. It is very difficult to assess the value equitably as between the Government and the owner. When the general system of supply becomes available it is perhaps reasonable that the capital which the owner has invested in these local plants should be protected. It is not, however, reasonable that this capital should be fully protected and that at the same time the owner should get full advantage of the Government supply whilst not conforming completely to the policy which has made that supply possible.

Factors that need consideration are—

(*a*) The value of the plant to the general system as an insurance against interruption to supply or shortage of power. It may have capacity in excess of the owner's own requirements, at least during certain periods of the day or year.

(*b*) The special value of the plant to the supply authority as insurance against interruption in its own supply from the Government.

(*c*) The degree to which the plant has been, or should have been, written off by reason of its having been rendered obsolescent by the scheme of general supply.

(*d*) The cost of operation of the plant apart from capital charges.

(*e*) The extent to which it could be used to reduce peaks, and the consequent saving in cost to the supply authority (purchasing on the maximum-demand rate) and reduction in revenue to the Government by such use.

(*f*) The remaining resultant total cost to the supply authority of the total power used by it, after paying for Government power plus capital charges on its own plant or part thereof.

Capital Expenditure.

The total capital invested by public supply authorities on the 31st March, 1933, was £32 546 205; of this, £12 046 552 represents expenditure by the Government, and £20 499 653 by various supply authorities. The rate of expenditure for the past 12 years is shown in Fig. 6.

A portion of the total represents capital spent on works

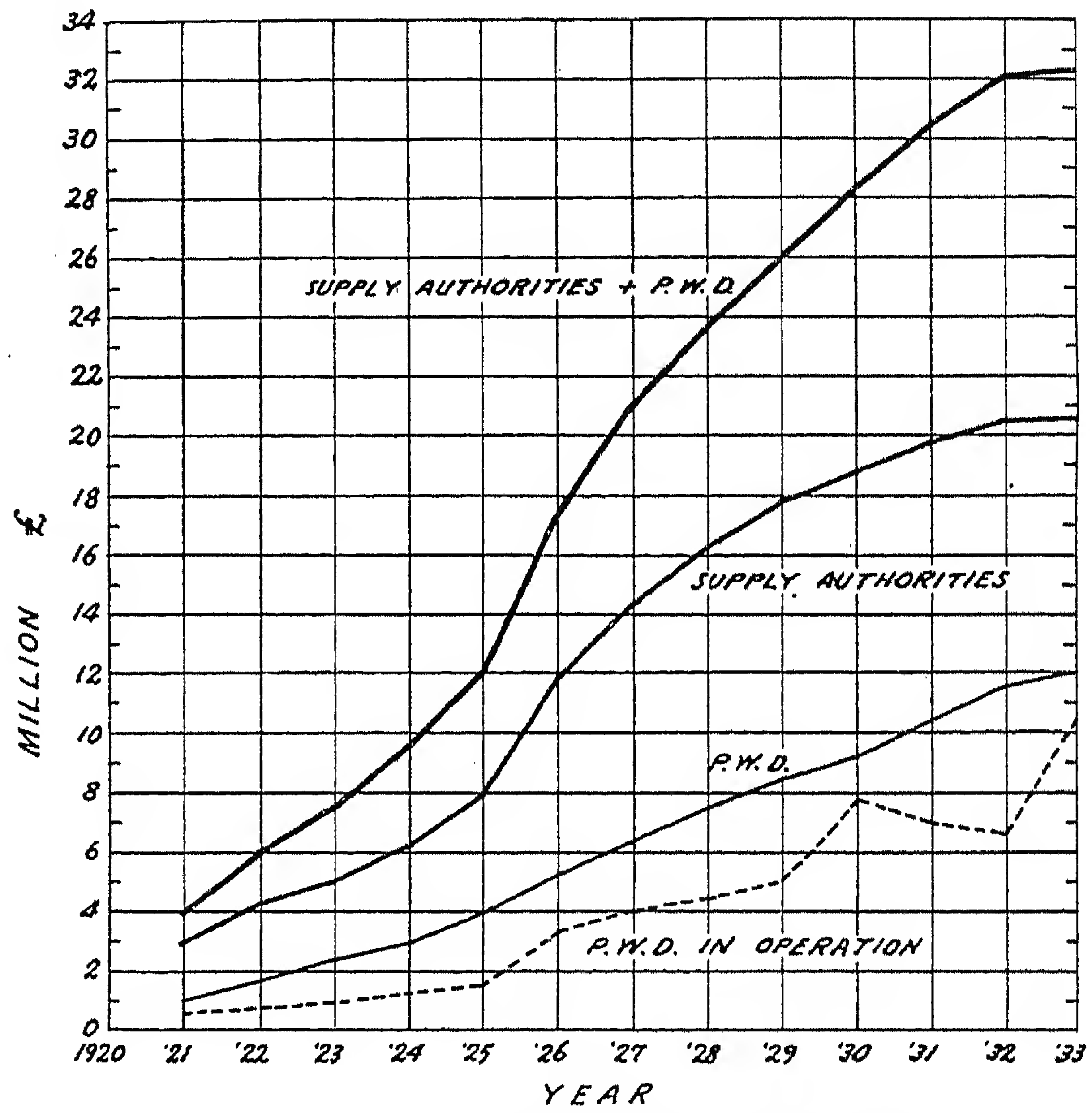


Fig. 6.—Total capital invested, 1920–1933.

still under construction but not yet operating. This is of considerable importance in connection with the Government portion of the total; the latter is mainly concerned with generation, transmission, and main substations, which may be several years under construction before reaching the stage at which they can be used. With the supply authorities, where capital is mainly spent on distribution lines which normally come into operation practically within the year in which the capital is spent, the difference between total capital and capital in operation is not so large or of such importance. Under the Government scheme of accounting, interest on works under construction is capitalized until such time as the work goes into operation. The drop in the line representing operating capital in the graph during the years 1931 and 1932 needs some explanation. It is due to the fact that the Arapuni power plant, after operating for a period of a little over a year, was forced to go out of action for a further period of nearly two years whilst repairs to a section of the

head-race were being executed. During that period, capital charges on the headworks and such portions as were not capable of being used, were again capitalized.

Earning Capacity of Government Scheme.

The percentage of total operating capital at the end of each year available to pay interest, depreciation, and sinking fund, on the combined Government schemes, after paying operating and maintenance charges, is shown in Fig. 7.

The result may be summarized up to the 31st March, 1933, by stating that since the inception of Government supply in 1915 the various schemes have paid all operating charges and interest on money borrowed, and have, in addition, been able to place £339 983 to the credit of a depreciation fund, £284 533 to the credit of the sinking fund, and £195 475 to a general reserve.

Reliable statistics over a period of years relating to other supply authorities are not available, but judging by results that are available over the past three or four

FIG. 7.—Percentage earned on operating capital (1915–1933) after paying net operating expenses.

years there can be no question that on the average the business has been a highly profitable one. This is particularly applicable to the main cities.

For the past year alone, electricity supply undertakings, other than the Government, as a whole, paid all operating costs, paid 7·18 per cent on all capital, and provided a surplus of £295 000.

This capital expenditure must, however, be looked at from other points of view. Considered by itself, it appears to have gone ahead by leaps and bounds without much reason.

Capital per Consumer.

Fig. 8 shows the capital expenditure in pounds sterling per consumer, and indicates that the rate of increase, although still considerable, is not nearly so great as in the graph of total capital expenditure, and is, moreover, increasing only at a reducing rate, particularly in the case of the supply authorities.

Considered again in terms of pounds of capital expenditure per pound of revenue, it will be seen that, although for a few years from 1921 to 1926 there was a slight increase in capital expenditure, since that date the capital per £ of revenue shows little increase and will probably gradually decrease in the future.

The increase in capital outlay per consumer is, in the main, due to the very much larger proportion of country area supplied, and partly to the increasing demand per head, and also largely to the fact that many parts of the

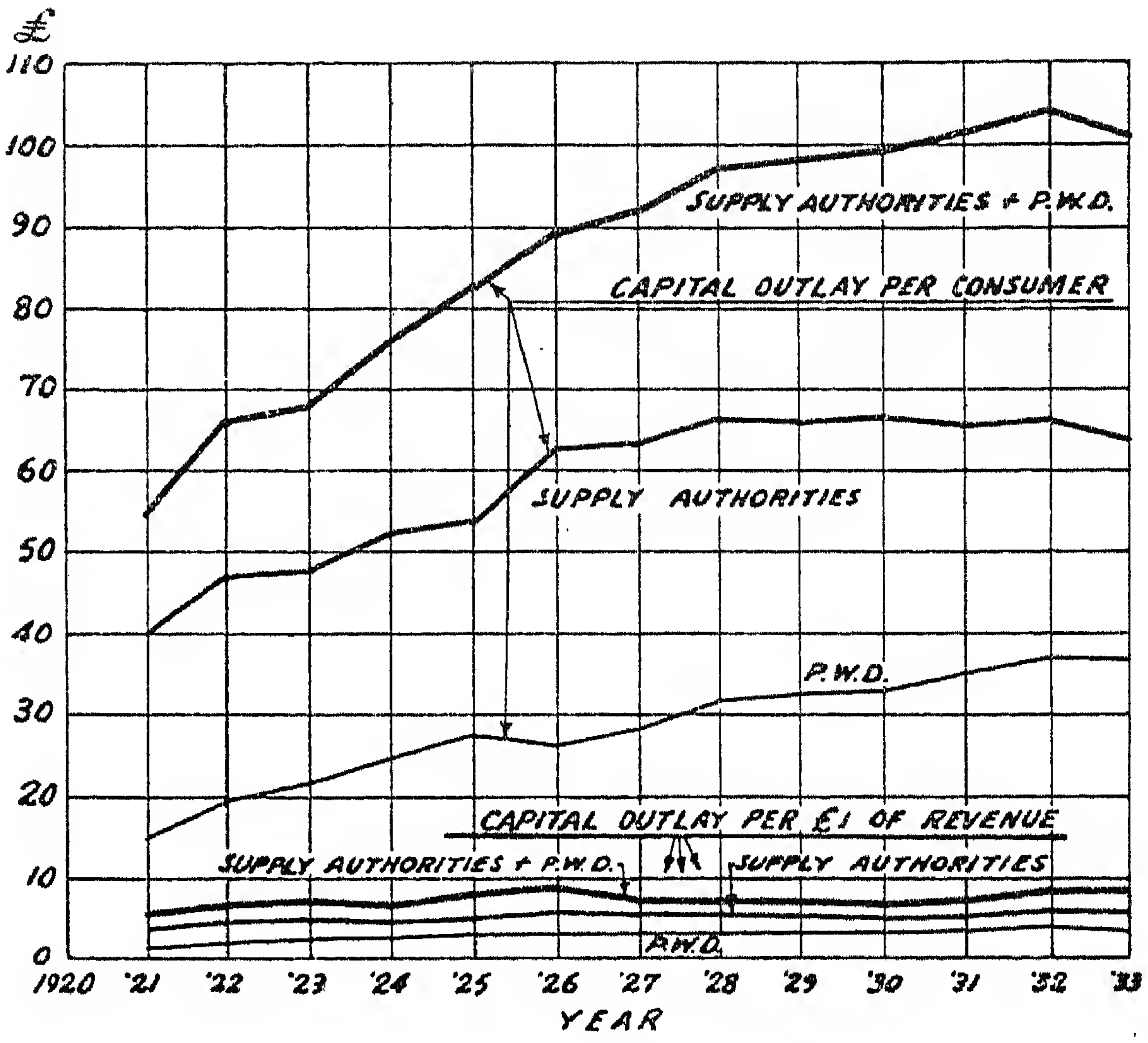


FIG. 8.—Capital outlay, 1920–1933.

system are in excess of present requirements so that considerable increments of load can be met with comparatively small increase in cost.

Consumers per Mile, and Revenue per Consumer.

Fig. 9 shows the number of consumers per mile of line and the average revenue per consumer. This indicates how, with the reticulation spreading out into the country districts during the years 1920 to 1926, the number of consumers per mile fell rapidly from 32 to the present figure of 15. In spite of this it will be found in a later

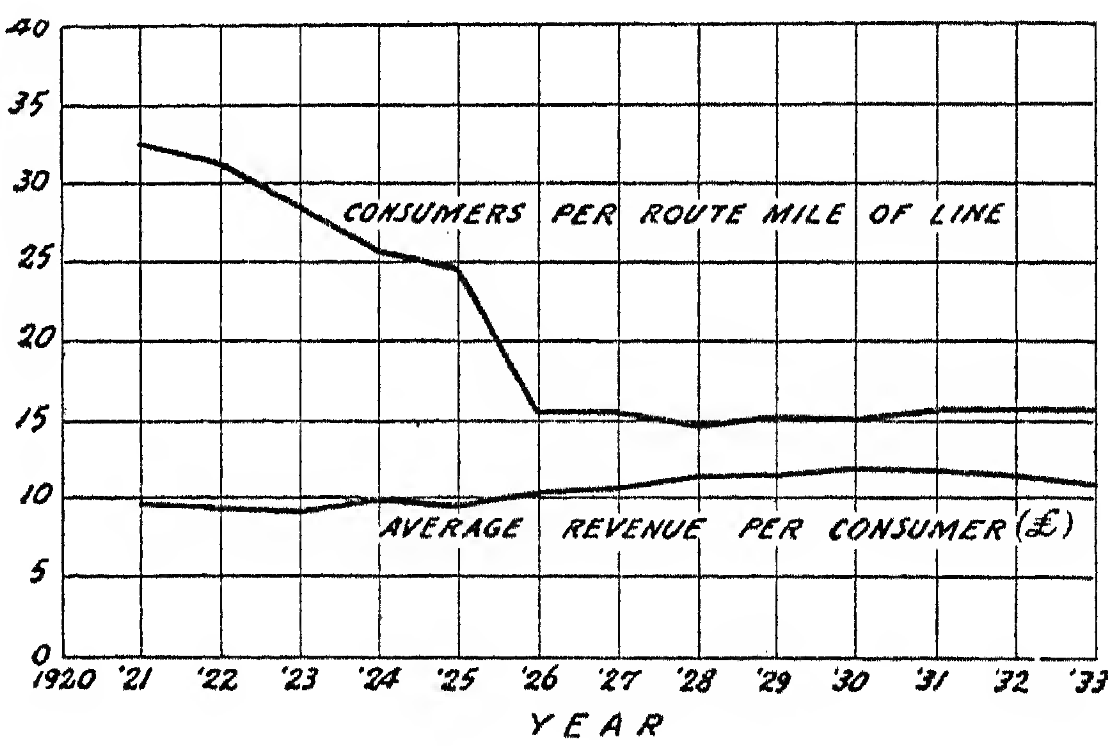


FIG. 9.—Consumers per route mile of line, and average revenue per consumer, 1920–1933.

diagram that, following a temporary rise in the average revenue and cost per unit, these averages have now come down below those holding in 1920.

The average revenue per consumer has shown a slight

tendency to vary from £10 up to £12 and down again to £11 in the last two years of depression.

Revenue per Mile of Line.

In the same way as the consumers per mile of line dropped away as Power Boards with rural reticulation came into operation, so also the revenue per mile also fell away (see Fig. 10). In 1921 there were only 2 570 route miles of line in operation, supplying, of course, mainly urban and suburban districts. This gradually increased to 6 011 miles by 1925, and then quickly increased to 12 454 by the end of the next year, when a number of the Power Boards supplied by the Mangahao system, and also additional ones in Waikato and Canterbury, came into operation. During more recent years the mileage of lines has been steadily increasing until it is now 20 585. In 1921 each mile of line earned a revenue of £260; this gradually decreased to £240 per

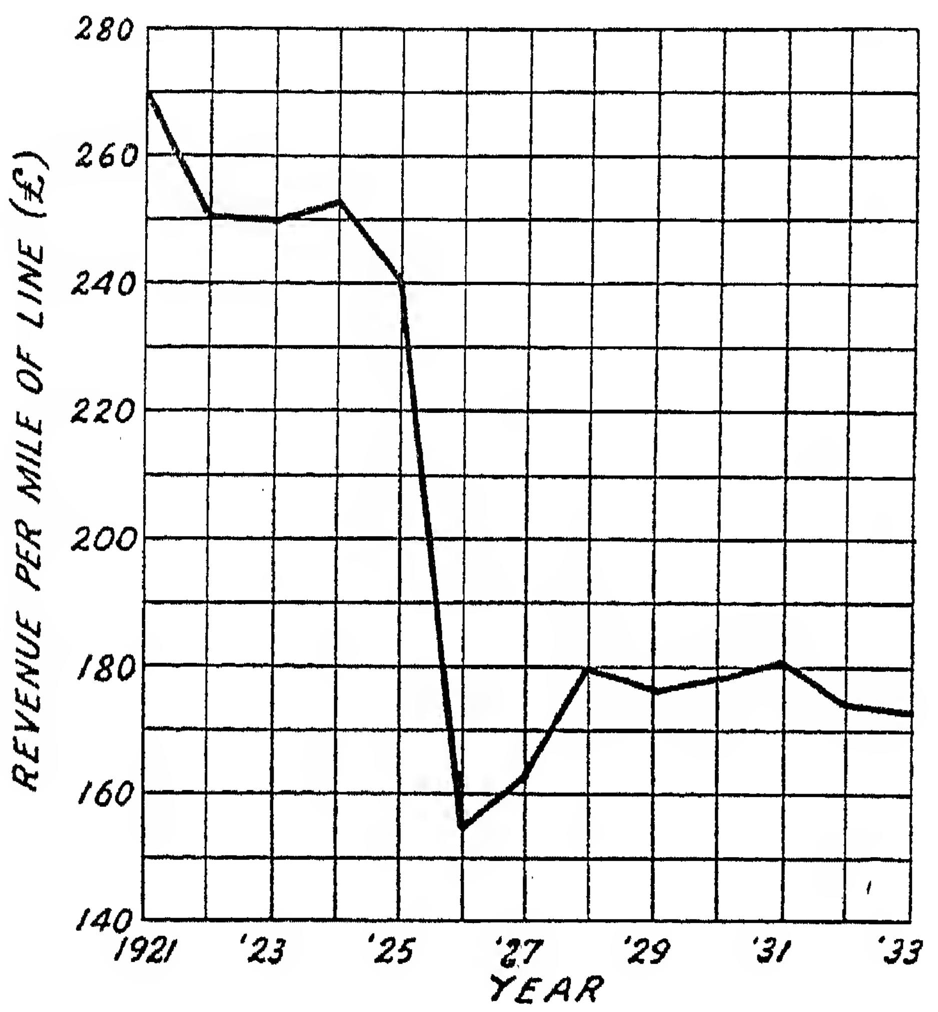


FIG. 10.—Revenue per mile of line, 1921–1933.

mile in 1925, and then fell suddenly to only £156 per mile in 1926, following the big increase in operating mileage during that year. As these lines gradually became loaded, the revenue gradually crept up to about £180 per mile, although the average revenue per unit was gradually falling all the time. More recent years show a fairly constant revenue per mile at about that figure. There has been a slight drop during the past two years, due partly to decreased revenue per unit with falling prices and partly to decreased demand owing to prevailing conditions.

The above are average figures and are compiled from very variable returns from different supply authorities. Some of the urban areas are able to show very much higher figures, whilst those for some of the rural areas are very considerably lower. For example, the following figures might be quoted:—

Christchurch ..	£645	per mile for	322·5 miles.
Palmerston North ..	£695	,, ,,	81·5 ,,
Napier	£1 177	,, ,,	36 ,,
Wellington	£1 020	,, ,,	306 ,,

and on the other side

Malvern Power Board..	£39	per mile for	182 miles.
Ashburton Power Board	£49	,, ,,	870 ,,
Southland Power Board	£49	,, ,,	2 395 ,,
Wairere Power Board..	£44	,, ,,	112 ,,

Costs and Revenue on a Unit Basis.

More assuring still, however, is Fig. 11, which shows the annual capital costs, annual working costs, and average revenue per unit sold.

The revenue shown is the average revenue per unit from retail sales to the actual consumer, and excludes all revenue from wholesale sales to other supply authorities for resale.

The full lines represent the total cost and total revenue, and also the total capital cost per unit and total working cost per unit, being the sum of the costs of the Government and supply authorities whose individual costs are

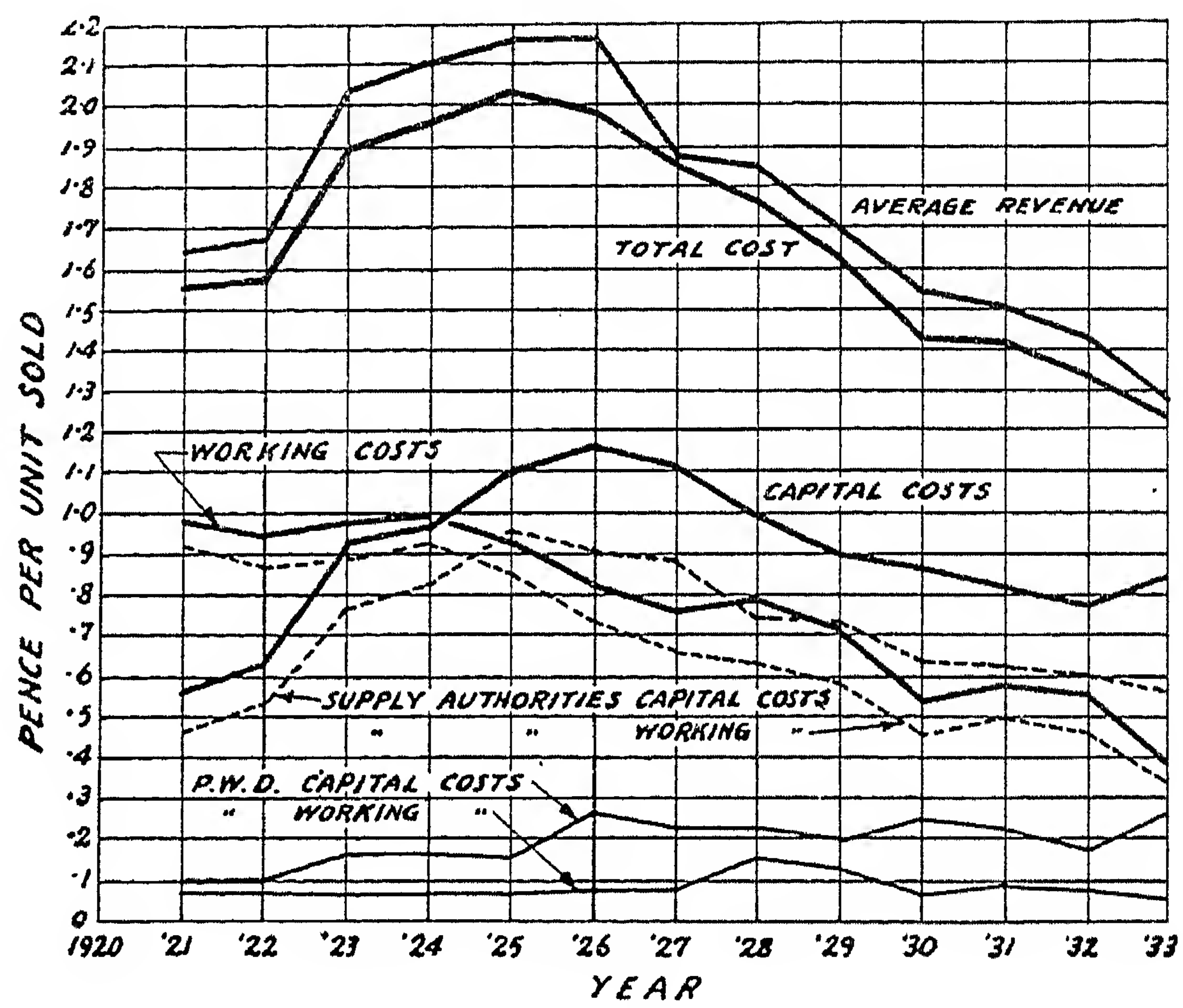


FIG. 11.—Relation between revenue and cost per unit sold, 1920–1933.

represented by the lighter lines, and the dotted lines respectively, on the same diagram.

It will be noted that the capital costs per unit show a considerable increase between 1921 and 1926, as was shown in the capital cost per consumer, and as was suggested by the graph of consumers per mile. The operating costs, however, show a decided reduction, almost continuously from 1921 to 1932. As a result, although from 1921 to 1926 it was necessary and possible to obtain a gradually increasing revenue per unit, since that date it has been possible to bring down the average revenue per unit until it is now well below the 1921 figure. The average revenue per unit for all purposes is now 1·28d. per unit. The average consumption per consumer for all purposes is 1 970 units.

Relation between Cost of Energy and Consumption.

The decrease in unit cost with increased consumption is clearly illustrated in Fig. 12, which has been compiled from the returns of all the supply authorities in New Zealand.

In Fig. 12 each dot represents the average price per unit and the number of units per consumer, for one supply authority.

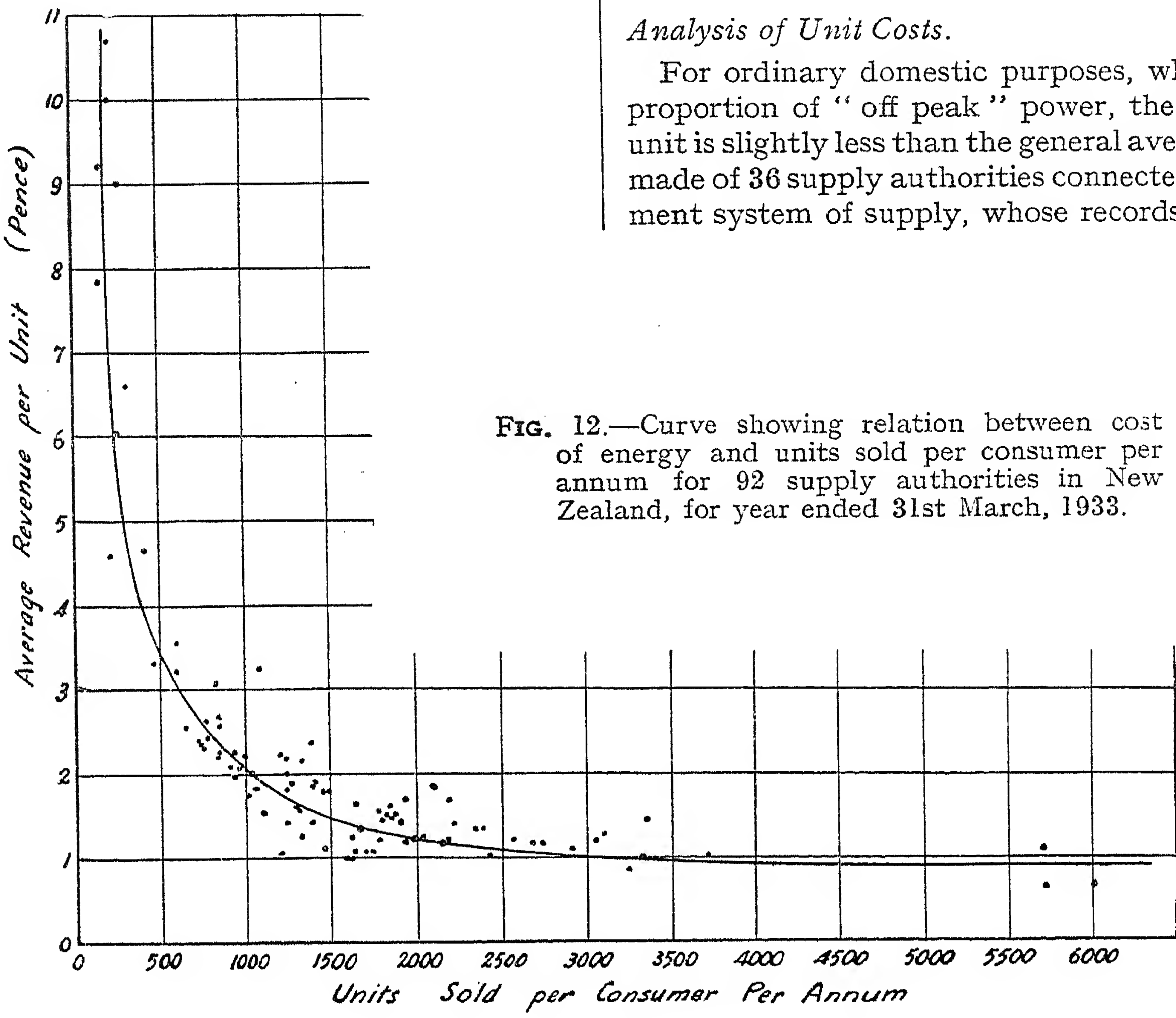


FIG. 12.—Curve showing relation between cost of energy and units sold per consumer per annum for 92 supply authorities in New Zealand, for year ended 31st March, 1933.

The general shape and scale of this graph follows closely that given by J. M. Kennedy and Dorothy M. Noakes for English conditions.*

Analysis of Unit Costs.

For ordinary domestic purposes, which include a fair proportion of "off peak" power, the average price per unit is slightly less than the general average. An analysis made of 36 supply authorities connected with the Government system of supply, whose records give the required figures, show the average cost per unit for ordinary domestic purposes to be 1·143d. per unit. This figure of 1·143d. is analysed in Fig. 13 into the principal items which go to make up the total cost.

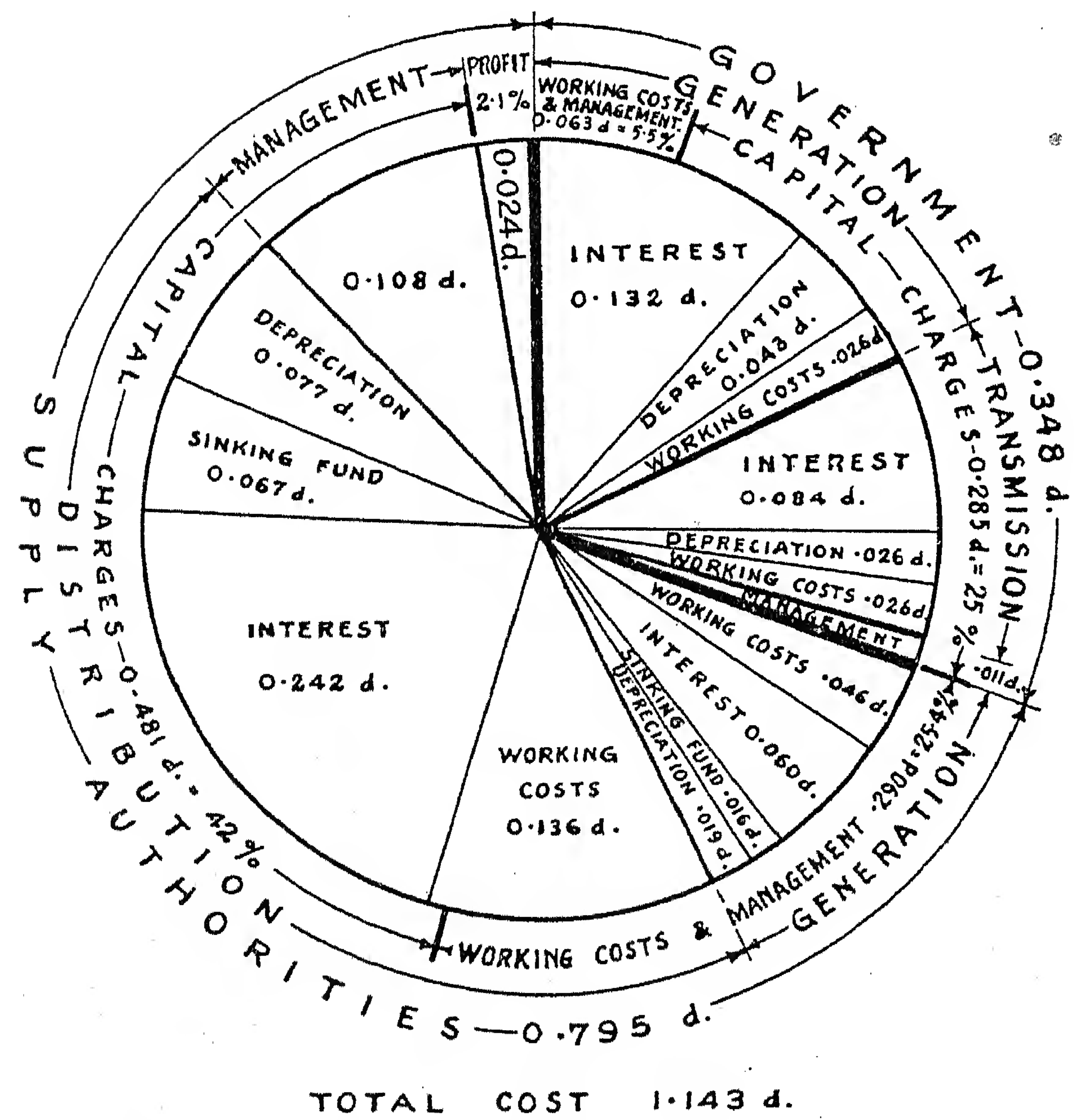


FIG. 13.—Cost of energy for domestic use. Average of 36 authorities supplied by Government.

The very small consumption per consumer when the average price per unit is much above $2\frac{1}{2}$d. and the gradual decrease as the consumption increases, is very evident.

About 30 per cent of the total cost represents the cost of bulk supply from the Government, and 70 per cent the supply authorities' costs.

Such comparisons as the author has been able to make with English and with American figures seem to indicate that, under New Zealand conditions, the proportion representing generating charges is comparatively lower, and the proportion representing distribution costs somewhat higher, than in the other cases.

It is claimed that the New Zealand system has been designed on comprehensive lines, and that the present costs can be considerably reduced as the consumers per mile of line and the consumption per consumer increase. It is claimed also, considering that the average density of population of the reticulated areas, including the cities and towns, is only 70 per square mile, the consumers only 15 per square mile, and that there are comparatively few large manufacturing industries absorbing large blocks of power, that the system has been successful in that it has made power available to a very large proportion of the total population at a reasonable cost. There may have been mistakes; improvements can, and undoubtedly will, be made, but New Zealand claims to hold a high place amongst those countries in which electricity is widely used.

* *Journal I.E.E.*, 1933, vol. 73, p. 97.

APPENDIX.

CLASS "A" CONTROLLING AUTHORITIES (*see* Table 1, page 69).

Power Board				Included Boroughs and Town Districts (T.D.)		Remarks
Name	Reference No. on Map (S. South Island; N. North Island) (1)	Population (includes Boroughs in Col. 4) (2)	Capital investment (3)	Name (4)	Population (5)	
(1) Ashburton	S.12	18 700	£ 357 784	Ashburton Boro. Tinwald T.D.	5 450 700	Small plant used for peak-reducing
(2) Auckland	N.6	225 000	3 406 366	Auckland City Onehunga Boro. One Tree Hill Boro. Otahuhu Boro. Mt. Albert Boro. Newmarket Boro. Mt. Eden Boro. Ellerslie T.D. Howick T.D. Papatoetoe T.D. Manurewa T.D. Papakura T.D.	106 300 11 200 8 050 5 050 20 750 3 250 20 100 2 800 650 2 130 1 500 1 780	Board's steam plant subsidized by Govt., and operated only at request of Public Works Dept.
(3) Banks Peninsula	S.15	4 050	103 187	Akaroa Boro.	600	
(4) Cambridge	N.32	6 000	110 234	Cambridge Boro. Leamington T.D.	2 150 570	
(5) Central Waikato	N.33	19 010	348 204	Huntly Boro. Ngaruawahia Boro. Raglan T.D. Te Kauwhata T.D.	1 940 1 260 360 480	Hamilton Boro. adjoins this area but buys direct from Public Works Dept.
(6) Central Hawke's Bay	N.22	11 500	138 344	Waipukurau Boro. Waipawa Boro.	2 000 1 190	
(7) Dannevirke	N.21	12 614	213 820	Dannevirke Boro. Woodville Boro. Ormondville T.D. Norsewood T.D.	4 550 1 120 290 180	
(8) Franklin	N.7	17 101	288 790	Pukekohe Boro. Waiuku T.D. Tuakau T.D. Mercer T.D.	2 520 880 680 340	
(9) Horowhenua	N.17	17 150	212 293	Foxton Boro. Levin Boro. Otaki Boro. Shannon Boro.	1 750 2 710 1 630 1 170	
(10) Hutt Valley	N.18	44 100	386 414	Upper Hutt Boro. Lower Hutt Boro. Petone Boro. Eastbourne Boro. Johnsonville T.D.	3 700 14 250 11 150 2 070 1 600	Wellington City adjoins but there is a fairly clear line of demarcation between
(11) Malvern	S.13	5 050	65 098	—	—	
(12) Poverty Bay	N.27	24 440	331 474	Gisborne Boro. Te Karaka T.D. Patutahi T.D.	14 350 400 290	Board owns generating plant which can be used to cut peak
(13) Springs-Ellesmere	S.14	12 330	156 085	Southbridge T.D. Leeston T.D.	430 660	
(14) Tararua	N.20	8 115	164 559	Pahiatua Boro. Eketahuna Boro.	1 500 770	
(15) Te Awamutu	N.31	7 650	186 023	Te Awamutu Boro. Ohaupo T.D. Kihikihi T.D.	1 870 240 320	
(16) Wairarapa	N.19	19 500	359 291	Masterton Boro. Carterton Boro. Featherston Boro. Martinborough Boro. Greytown Boro.	8 700 1 920 1 120 1 040 1 140	Board's own small generating plant operated by arrangement with Public Works Dept.
(17) Waitaki	S.10	19 500	179 341	Oamaru Boro. Hampden Boro.	7 600 250	Board owns generating plant which can be used to cut peak
(18) Waitemata	N.5	40 485	397 524	Devonport Boro. Takapuna Boro. Birkenhead Boro. Northcote Boro. New Lynn Boro. Helensville T.D. Henderson T.D. Glen Eden T.D.	10 400 7 000 3 400 2 540 3 290 1 020 1 110 1 320	
(19) Waitomo	N.10	8 000	100 210	Te Kuiti Boro. Otorohanga T.D.	2 530 690	

CLASS "B" CONTROLLING AUTHORITIES (*see* Table 1).

Power Board				Boroughs and Town Districts operating own reticulation						(c) Boroughs, etc., functioning as part of Board		
				(a) In district			(b) In outer area					
Name	Reference No. on Map (S. South Island; N. North Island)	Population, including boroughs in Col. (c) only	Capital investment, excluding capital in (a) and (b)	Name	Popu-lation	Capital	Name	Popu-lation	Capital	Name	Popu-lation	Remarks
			£			£			£			
(1) Bay of Plenty ..	N.28	8 700	209 089	—	—	—	Whakatane Boro.*	1 800	37 823	Opotiki Boro.	1 310	
(2) Hawke's Bay ..	N.23	16 720	219 776	Napier Boro.* Hastings Boro.*	18 000 12 713	170 932 118 791	Havelock North T.D.*	1 100	24 074	Taradale T.D.	1 170	Napier and Hastings plants closed down by arrangement
(3) Manawatu-Oroua ..	N.16	39 011	512 150	Palmerston Nth. City*	22 850	220 127	—	—	—	Feilding Boro. Rongotea T.D.	4 450 280	Palmerston plant operates to cut peak
(4) North Canterbury ..	S.16	9 064	143 122	—	—	—	Kaiapoi Boro. Rangiora Boro.	1 700 2 100	10 701 12 862	—	—	
(5) South Canterbury ..	S.11	24 598	325 565	Timaru Boro.	18 000	135 390	—	—	—	Temuka Boro. Geraldine Boro. Waimate Boro. Pleasant Point T.D.	1 900 1 000 2 300 580	
(6) Thames Valley ..	N.30	34 685	825 634	Thames Boro.* Te Aroha Boro.*	4 750 2 550	24 156 25 896	—	—	—	Waihi Boro. Morrinsville Boro. Paeroa Boro. Matamata T.D. Putaruru T.D. Turua T.D.	3 040 1 740 1 940 1 170 870 280	Waihi Boro. in outer area
(7) Wairoa	N.26	5 520	62 461	Wairoa Boro.	2 400	12 589	—	—	—	—	—	
(8) Wanganui-Rangitikei	N.15	52 000	562 841	Taihape Boro.* Mangaweka T.D.	2 450 415	18 924 5 710	—	—	—	Wanganui City* Marton Boro. Hunterville T.D. Bulls T.D. Waverley T.D.	25 000 2 850 640 550 660	Board's own steam plant at Wanganui operates only by arrangement with Public Works Dept.
(9) South Taranaki ..	N.14	16 280	196 031	—	—	—	Patea Boro.*	1 800	17 229	Hawera Boro. Normanby T.D. Manaia T.D.	4 730 360 720	Board also generates power in own plant

* Own generating plant.

CLASS "C" CONTROLLING AUTHORITIES (*see* Table 1).

Power Board				Included Boroughs or Town Districts		
Name	Reference No. on Map (S. South Island; N. North Island) (1)	Population, inclusive of Boroughs, etc., in Col. 4 (2)	Capital Investment (3)	Name (4)	Population (5)	Remarks
			£			
Golden Bay	S.21	1 200	25 788	Takaka T.D.	430	Generates own power
Grey	S.3	13 250	283 579	Brunner Borough Greymouth Borough Runanga Borough Cobden T.D.	720 6 250 1 470 1 240	Generates own power
Opunake	N.13	6 000	108 994	Opunake T.D.	1 020	Generates own power, supplemented by bulk purchase from New Plymouth
Otago	S.7	17 931	283 712	Palmerston Borough Waikouaiti Borough Lawrence Borough Balclutha Borough Kaitangata Borough Naseby Borough Milton Borough Mosgiel Borough	800 600 650 1 610 1 380 200 1 570 2 080	Board purchases power from Dunedin City Milton in outer area Mosgiel in outer area but supplied by Dunedin City
Teviot	S.8	1 800	57 958	Roxburgh Borough	430	Generates own power; also sells in bulk to Otago Central Power Board
Otago Central	S.9	2 537	89 433	Alexandra Borough Cromwell Borough	650 600	Board purchases power from Teviot Power Board but is contemplating construction of own hydro-electric generating station
Wairere	N.9	2 000	42 006	None	—	Generates own power

CLASS "D" CONTROLLING AUTHORITIES (*see* Table 1).

Power Board: Name	Power Board: Reference No. on Map (S. South Island; N. North Island)	Power Board: Population, including boroughs in (c) only	Power Board: Capital, excluding capital in (a) and (b)	Boroughs and Town Districts operating own reticulation: (a) In district: Name	(a) In district: Population	(a) In district: Capital	(b) In outer area: Name	(b) In outer area: Population	(b) In outer area: Capital	(c) Boroughs, etc., functioning as part of Board: Name	(c): Population	Remarks
			£			£			£			
Marlborough	S.19	14 530	322 537	—	—	—	Picton Boro.*	1 310	19 380	Blenheim Havelock	5 300 230	Generates own power
Southland	S.6	48 250	1 660 102	Invercargill City* Bluff Boro.	21 000 1 700	176 256 10 810	—	—	—	Winton Wyndham Edendale Riverton Gore Nightcaps Otautau Tapanui Lumsden Mataura	930 680 470 930 4 260 700 650 290 530 1 320	Generates own power
Taranaki	N.12	13 985	456 941	—	—	—	Stratford Boro. Waitara Boro. Inglewood Boro. Kaponga T.D.*	3 500 1 850 1 300 1 200	27 843 12 655 12 644 24 507	Eltham	2 010	Generates own power. Contract with Government for partial supply if required
Tauranga	N.29	8 490	132 191	—	—	—	Tauranga Boro.* Te Puke T.D.	2 850 980	155 367 12 384	Mount Maunganui	440	Tauranga Borough supplies Power Board in bulk
Westland	S.4	4 200	69 300	—	—	—	Hokitika Boro. Ross Boro.*	2 520 450	(Kanieri Electric, Ltd.) Not known	—	—	Hokitika reticulated by Kanieri Electric, Ltd.
Waimea	S.20	4 000	22 823	Motueka*	1 750	16 697	Nelson*	11 500	112 890	Richmond Tahunanui	1 160 760	

* Own generating plant.

CLASS "E" CONTROLLING AUTHORITIES (*see* Table 1).

Supply authority: Name	Supply authority: Population, includes (b)	Supply authority: Capital, excludes (a)	(a) Gives supply in bulk to Boroughs or Town Districts: Name	(a): Population	(a): Capital	(b) Retails in area of Boroughs or Town Districts: Name	(b): Population	Remarks
		£			£			
Nelson City	11 500	112 890	Waimea Power Board*	4 000	22 823	—	—	Supplies part only of Power Board's requirements
Dunedin City	92 000	1 710 617	Otago Power Board	17 931	283 712	Port Chalmers West Harbour St. Kilda Green Island Mosgiel Outram	2 570 2 100 8 250 2 400 2 080 340	Has contracted to take part supply from Government
Kanieri Electric, Ltd.	2 520	97 335	—	—	—	Hokitika	2 520	
New Plymouth Borough	21 000	441 487	Opunake Power Board* (part only)	6 000	108 994	—	—	Takes part supply from Government
Taumarunui Borough	4 000	62 219	Manunui Town District	850	3 290	—	—	
Tauranga Borough	2 850	155 367	Tauranga Power Board Te Puke Town District	8 490 980	132 191 12 384	—	—	
Wilson's (N.Z.) Portland Cement Co.	510	92 133	Whangarei Borough Kamo Town District	7 790 600	68 072 3 579	—	—	
Christchurch City (purchases in bulk from Government)	95 000	808 996	—	—	—	Riccarton (part only) New Brighton	5 200 4 860	

* Own generating plant.

CLASS "F" CONTROLLING AUTHORITIES (*see* Table 1).

Supply Authorities other than Power Boards supplied direct by the Government.

Name	Population	Capital investment
		£
(1) Christchurch City	95 000	808 996
(2) Dunedin City (part only) (contract arranged) ..	92 000	1 710 617
(3) Hamilton Borough	15 500	76 511
(4) Heathcote County	6 000	36 648
(5) Lyttelton Borough	3 710	10 990
(6) New Plymouth Borough (part only)	21 000	441 487
(7) Riccarton Borough	5 500	23 927
(8) Sumner Borough	3 500	16 975
(9) Waimairi County	13 000	84 610
(10) Wellington City	110 000	1 193 035

CLASS "G" CONTROLLING AUTHORITIES (*see* Table 1).

Supply Authorities in Isolated Districts generating their own power.

Name of supply authority	Population	Capital investment
		£
Whakatane Borough Council	1 800	37 823
Ohakune Borough Council	1 940	18 674
Kaikoura County Council	630	10 107
Murchison County Council	500	13 925
Westport Borough Council	4 000	31 716
Uawa County Council	400	6 275
Reefton Electric Light Co.	1 300	5 848
Raetihi Borough Council	4 500	37 636
Queenstown Borough Council	845	12 870
Alderton Utility Co.	280	5 439
Havelock North Town Board	1 163	24 074

Discussion before The Institution, 20th December, 1934.*

Prof. W. M. Thornton: It seems to me that New Zealand is an example of where the supply has created the demand. It is not like Canada, where there are large industries taking great bulk supplies; New Zealand is an agricultural country, and coal has largely to be imported. There are immense potential water-power resources in New Zealand, and I should say that not one-tenth of the available water power has been utilized.

The difficulty in New Zealand is that at the moment the demand is insufficient. If cheap power can cause industry, as we so often hear, then one can foresee that in the course of 100 years New Zealand will be one of the great manufacturing districts of the Empire. At any rate, it will make all that it wants for itself. One point which ought to be borne in mind in thinking about this paper is that the conditions in New Zealand are different from those of any other country in the world. The South Island of New Zealand is a mixture of the Highlands of Scotland, Switzerland, Norway, and the South Downs. The North Island is semi-tropical with a lot of heavy tree and bush country, and there is a great bare patch in the middle which is barren ground. When I was out there it was said to me—I do not know with what truth—that all that district wanted in order for it to become a great agricultural area was fertilizers. I replied " You have, or will have shortly, the two great elements for the manufacture of fertilizer. In the first place all this forest district which you have here will have to be thinned, and therefore you will have great surplus quantities of carbon; and on the other hand the water power, which is just about to be developed, will give you your electrical supply. What about the electrical manufacture of calcium cyanamide, which is one of the fertilizers which you want? It is at your door." I made that statement to Sir William Fraser in 1914, and as far as I know nothing has yet arisen from it. Now that New Zealand has supplies of electrical power, and now that she wants to utilize them, it might be worth reviving the idea whether it would not be cheaper for her to arrange to have fertilizers made electrically in her own

* The paper was presented at the meeting by Mr. W. P. Gauvain on behalf of the author.

country than to import them. The conditions for making electrochemical products are now much better than they have ever been before; and New Zealand does want some manufactures of that kind.

Mr. W. P. Gauvain: In 1911 Mr. Evan Parry, a member of the Institution, went out to New Zealand as chief electrical engineer of the Public Works Department. He was responsible for formulating a scheme for electrical distribution throughout the two islands. The supply systems shown in Figs. 1 and 2 are the outcome of the scheme which he formulated during the 8 years he was in New Zealand. Mr. Parry laid it down that the maximum demand he would allow per head of population was 0·15 kW, and it is interesting to know that—after about 14 years' work, when the whole country is not yet "reticulated"—that figure has been almost realized.

Those who have been in New Zealand will appreciate the troubles with which the engineers over there have had to contend. The civil engineering conditions are extremely difficult, owing to the treacherous nature of the ground, and in consequence estimates are often exceeded. Great difficulties have also been met with in the erection of the transmission lines. I have known cases where lines have had to be erected over mountainous country and through virgin forest where the trees range up to 100 ft. in height. The steel poles have had to be taken up in sections weighing not more than 160 lb. so that they could be carried by a pack horse, and the cables have had to be drawn out by bullocks. All this means very heavy expense. In connection with the 110 000-volt lines, I think that these were in use in New Zealand before lines of this voltage were used in this country. Great Britain owes something to New Zealand in that British manufacturers had the opportunity of experimenting with and designing 110 000-volt apparatus for New Zealand before they were called upon to design the 132 000-volt equipment for use in this country.

The Power Board legislation has proved extremely useful to New Zealand. The largest block supply of power is 3 000 kW—to a gold-mining company. All the other supplies of power are comparatively small. The chief consumptions are domestic, and the incidental power loads—which occur in towns; there are no large industries. The development has really been on the domestic and farming side. At the 31st March, 1934, there were 334 000 consumers in New Zealand, equipped with 36 000 cookers, over 50 000 water heaters, and 17 000 electrically-driven milking machines. Whereas one hears but little of milking machines in this country, no farmer in New Zealand who is milking more than about 20 cows does it by hand. This is quite a good load in the areas which the New Zealand Power Boards have developed.

With regard to finance, the capital outlay at present is nearly £100 per consumer. When the Power Boards were first started materials were costly and the price of money was very high; many of the Boards had to pay interest charges of over 6 per cent. Practically everything used by the Power Boards is imported into New Zealand, and in consequence the capital costs must be high when compared with the figures in a country like Great Britain. The exchange in New Zealand is now 100 English pounds to 125 New Zealand pounds, so that the actual cost of 1·143d. per unit in New Zealand coinage really works out at 0·914d. in our money.

In connection with the bulk-supply charges, I should like to know whether at the present time, after his experience of the last few years, the author still favours the system of having no unit charge. Would he prefer a small unit charge of about 0·1d., and a smaller kW charge, in place of the present charges? The method of bulk-supply charging adopted in New Zealand has produced extraordinarily good load factors. There is one Power Board which has a load factor of 76 per cent, and the average load factor of the whole of the Boards in New Zealand is about 56 per cent. There are 5 Power Boards with load factors of over 70, and 12 with load factors of between 60 and 70. We should be very glad if we could get such an average in this country.

Mr. W. A. Coates: In New Zealand, electrical distribution is mainly in the hands of Power Boards, who control the major part of the area. There are, however, still municipal supply undertakings, which operate very much in the same way as they do in this country. Both classes of authorities are members of the Association to which reference is made on page 65. I gather that there is some heartburning at the present moment over the question of the bulk-supply charges. Apparently some of the Power Boards whose areas are near the main generating stations feel that, because of that geographical advantage, they should be getting lower prices than some of their neighbours. Particularly do they resent the advantage which the municipalities have, because of their serving a much denser district. It remains to be seen whether any action will be taken to clear up that position. I am rather interested to note on page 64 the fact that a chairman of a Power Board may be paid not more than £300 per annum. I seem to remember that in the original Power Board Act no such limit was applied; £300 per annum is an extraordinarily small figure for what may be an onerous job, and one would be interested to know the explanation.

By far the most interesting feature of the paper, and of New Zealand's legislation controlling supply, is the rating provision, to which reference is made on page 64. About 80 per cent of the total rates collected lies at the door of one Power Board. I think it should be realized that that particular Board is operating in a district where the population density in the inner area (i.e. the area subject to rates) is only 14 to the square mile, and the consumer density is only 2·8 per square mile. Further, taking the whole of New Zealand, including the cities, the population density for the reticulated area is 66 per square mile. According to Messrs. Dickinson and Grimmett,* a figure of from 75 to 100 per square mile is the minimum which it is considered feasible to serve in this country. The New Zealand engineers have been much more adventurous, and their adventures have been justified.

The regulations set up and administered by the New Zealand Public Works Department are based almost entirely on the corresponding regulations in this country; and, from a mechanical point of view, a transmission

* *Journal I.E.E.*, 1932, vol. 70, p. 189.

line operating at 11 kV in New Zealand is a thing which would be passed in this country. The difference between the conditions in the two countries lies firstly in the fact that wayleave difficulties are almost unknown, and secondly that the Post Office does not enjoy any right of priority. The Post Office and the local electricity undertaker are on the same footing, and whichever gets there first has to keep its lines to one side of the road. The result of this is that, according to the reports of the Public Works Department, the average cost of building a 11-kV 3-phase line is £220 per mile. I have even known cases where a long line with a straight run over easy country has been built for very nearly £100 per mile less than that.

Fig. 12 in the present paper bears some resemblance to Fig. 6 in the recent paper by Mr. Kennedy and Miss Noakes,* although the two curves are actually plotted to different scales of abscissæ. Fig. A shows Fig. 12 plotted to the same base as Mr. Kennedy's Fig. 6. The two curves almost coincide, i.e. the conditions of the two countries are apparently almost identical. There seems to be at the present moment a popular feeling that something should be done to improve the methods adopted in connection with British distribution systems. Once again, therefore, I wish to make the suggestion that it would pay the electrical industry of this country to investigate the legal, the administrative, and the engineering methods which are being followed in New Zealand with regard to rural reticulation.

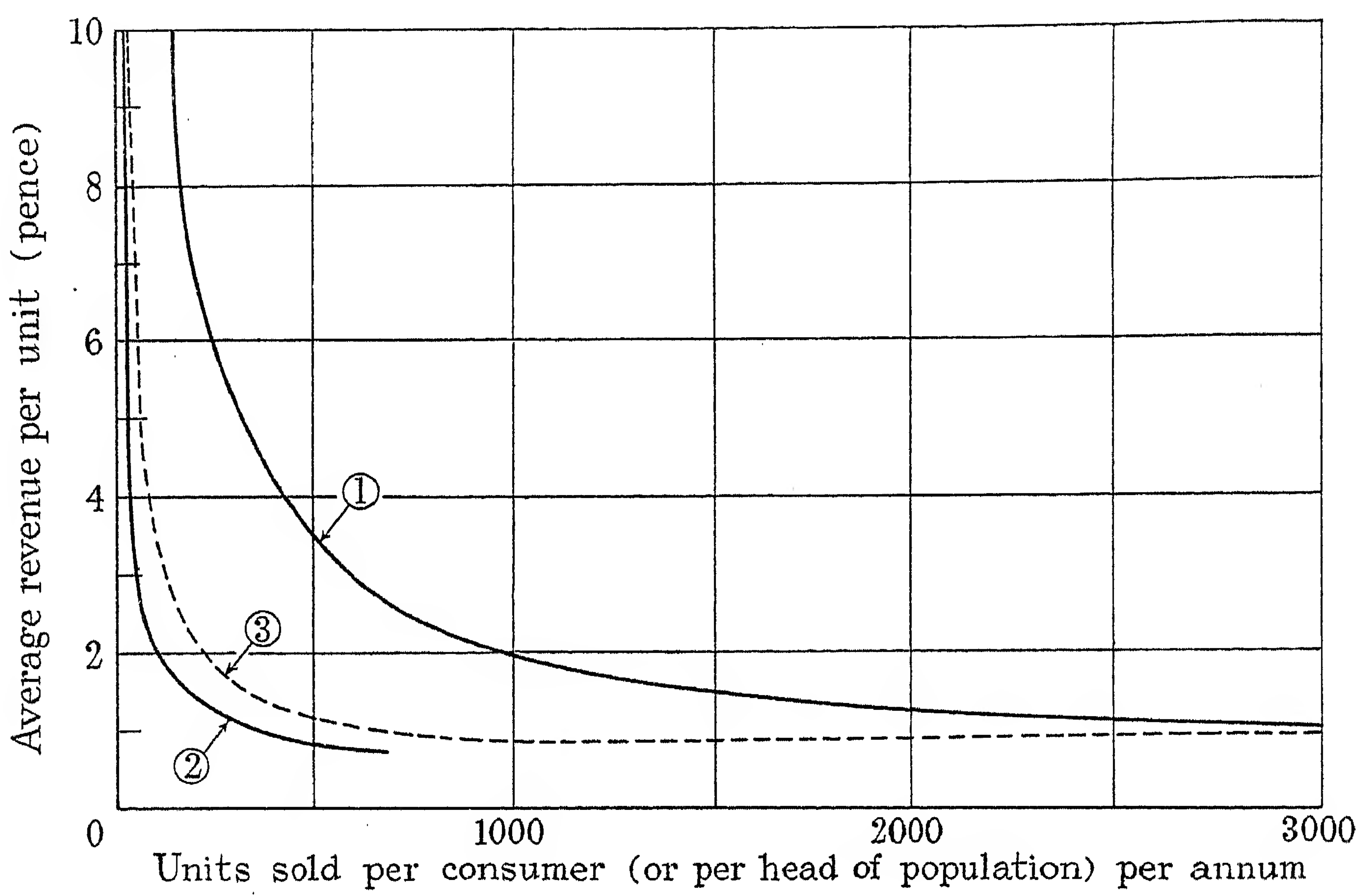


Fig. A.

Curve 1. From paper by Mr. Kissel (per consumer).
Curve 2. From paper by Mr. J. M. Kennedy and Miss Noakes (*per capita*).
Curve 3. Estimated curve for New Zealand (*per capita*).

Mr. E. E. Sharp: New Zealand has shown remarkable courage in spending 32 millions of capital for a population of only $1\frac{1}{2}$ millions, of whom only about half a million are actually wage-earners, and the country is to be congratulated on getting such wonderful results. It is of interest to mention that in many of the rural districts the maximum demand is actually built up by milking machines. In rural districts the water heaters, for instance, are arranged to be switched off for three separate peaks, two of which are brought about by milking machines, one of them in the very early morning.

A good deal of discussion is at present going on in New Zealand with regard to bulk-supply tariffs. New proposals are being put forward because, at present, no matter how small the Power Boards may be they have to pay a minimum annual charge. The smaller Boards say that this charge is pressing heavily upon them. They are trying to find some means of getting over that difficulty.

Mr. Gauvain has mentioned that New Zealand has 36 000 electric cookers in operation; this figure is very high in view of the smallness of the country, but it should be remembered that throughout the country there are about 154 000 gas cookers in operation. This suggests possibilities of a great deal of advance in the direction of electric cooking. What is surprising is to find that the New Zealand engineer at present does not seem inclined to do anything to make it easier for the consumer to introduce current-consuming devices into the home. I think perhaps New Zealand is a little too proud of the fact that up to now the workers have always been willing to buy their domestic apparatus. I was recently informed, in a letter from one of the Power Board engineers, that there could be no question of hiring out; that the workman was so much better off in New Zealand than in this country that it was quite easy to sell the apparatus to him. I do not feel that that outlook is justified, in view of the big difference between the numbers of electric cookers and of gas cookers. I suppose the number of wage-earners, namely half a million, is

* *Journal I.E.E.*, 1933, vol. 73, p. 103.

almost the same as the number of houses there are in New Zealand. The paper tells us that 96 per cent of the houses are within reach of a supply, so it would appear that there is a great field for increase of domestic consumption.

Mr. V. Z. de Ferranti: When I returned to this country 10 years ago after a visit to New Zealand I was disgusted to find that no one over here seemed to think that the countryside was worthy of being developed electrically. New Zealand, however, which has only two large towns—Auckland and Wellington—got on with the job of rural electrification, and was 10 years ahead of us. New Zealand is to be very much congratulated upon the splendid success of its projects, both technically and financially.

It has already been remarked that the New Zealand supply authorities were very helpful to British manufacturers. It is a fact that the first 110 000-volt power transformers to be made in this country were made for Mangahao, and I feel that it was a great act of faith on the part of the New Zealand authorities to give us that opportunity. It is gratifying to know that that faith was not misplaced.

Mr. A. N. D. Kerr: I have been trying, without success, to find out what specific remedy there is which, if applied to this country, would bring about such successful results as have been obtained in New Zealand. I have, however, much apprehension with regard to what is called the "availability rate," which represents 10 per cent of the total rates collected from the various ratepayers; is not this rather a large amount? I should like to know how much the Power Boards themselves pay back in rates to the local authorities. Presumably the Power Boards have to accept the valuation placed on them by the local authorities. With regard to the tariff, I infer from the paper that extremely attractive rates are quoted to consumers. Do these rates take the form of a capital sum, such as is quoted to Power Boards? Such a basis would seem consistent with supply by water-power undertakings. This type of tariff introduces a new conception into electricity charges, which has proved very successful in New Zealand; the conception being to charge only for the work involved in laying down the supply, much as water is sold in this country. It is not a system which can be successfully applied here, seeing that a great portion of the costs of electrical undertakings are based on running and distribution charges.

I do not see any reference in the paper to the counterpart in New Zealand of the British Electrical Development Association. How is it that 93 per cent of the population of New Zealand have been persuaded to take advantage of electricity supply?

I am interested in the registration of wiremen, and impressed by the fact that the Power Boards feel that they have a conscience in the matter and that they ought to listen to it. I do not know whether there are any inspectors of wiring in this country, similarly appointed and controlled by the supply undertakings; if there are, I have not heard of them. It seems that the Power Boards in New Zealand have realized that they are primarily responsible not only for the supply but also for the way in which it should be used. I am very interested to find that the New Zealand wiring regulations are based on those issued by the Institution. Are these regulations, with all their numerous onerous clauses, strictly enforced in New Zealand? If so, I cannot understand how it has been possible to carry out such cheap wiring.

Mr. William Wilson: The future of electrical engineering depends very greatly upon the efficiency with which the organization of power supply is carried out. Different types of organization are appropriate to the peoples of different countries, and it is particularly interesting to compare the methods which have been adopted in other English-speaking countries with our own. None of the previous speakers have said much as to the broad principles of the system described in the paper, and I should like to spend a little time in analysing these and comparing them with those of the system in Great Britain.

Both the conditions and the methods adopted in New Zealand are in several respects as different as possible from the state of things in this country. First, the conditions there cannot be said to render electric supply an easy matter. Great Britain has a high density of population and a cheap supply of coal, but the opposite is true of New Zealand. Each island has approximately the same area as England, and a population considerably less than that of the city of Birmingham; while although very good coal is obtainable, transport costs are responsible for the retail price being comparatively high. Secondly, the principles of organization are notably different. In Great Britain the keynote of electricity supply is centralization. The supply is operated by one authority, and all concerned have to obey instructions from headquarters. Again the opposite is true of New Zealand, since control is notably decentralized: where its services are not required, the chief authority does not interfere. It has its own stations and grid, and acts as a wholesale supplier when a supply is needed; but, except as the co-ordinating authority, it does not intrude where a district can look after itself. Furthermore, it does not concern itself at all with distribution and selling. It is for this purpose that the very successful scheme of Power Boards has been brought into being. Now the success of a decentralized system depends upon the aptitude of the people for efficient co-operation, and it cannot be denied that the New Zealand engineers and public have shown that they possess this faculty.

The great advantage of the Power Board method is that each function is entrusted to people to whose interests it is that their particular work shall be done to the best possible advantage. These boards are local bodies, constituted very much like an English county council, and what may be termed the retail distribution is put into their hands. They know their area thoroughly and are able to influence the prospective purchasers in order to secure the widest and most economical use for the electric power. They may have generating stations of their own, or they may purchase all or some of their power wholesale from the Government supply; and their function is to distribute it among consumers in the most effective manner. The very high load factors that they are able to command is in my opinion a sure indication as to the efficiency of their working, and must be due to

very successful encouragement of off-peak loads. No mention is made in the paper of methods whereby the load factor has been raised to so high a value, and I should like to ask for a few details as to the measures which have been adopted, such as the possible arrangement of peak loads to miss each other. The statement was made a few years ago that the great improvement required in this country was in load factor; I believe that the figure for Great Britain is still below 25 per cent, possibly about half the New Zealand figure, so that this information would be of special interest.

Another difficulty experienced in New Zealand is that so much of the country is occupied by dairy farms and other industries connected with the land, a type of consumer that it has proved very difficult to cater for in Great Britain. In New Zealand the difficulty must be even greater, because of the very large extent of many of the farms and the absence of other types of consumers in these areas. I should like the author to give some information as to the extent to which the farming industry have been induced to become consumers.

The recent legislation connected with wiring has been mentioned; I should like to know why so much more importance is attached to the standard of this work in New Zealand than in this country, especially as my own impression was that the standard in New Zealand as far back as 1915 was already higher than that some of us are familiar with here. It may be that the prevalence of wooden buildings and also the drier climate have increased the fire risks, but I am not certain whether there is not some other reason.

The author mentions the use of hydro-electric power in New Zealand: a year or two ago an account was given of a project for establishing a very big station at Lake Te Anau for supplying an electrochemical industry, largely for the purpose of producing nitrates. Nothing further has been heard over here about this scheme, and I should be interested to know what are the possibilities of this and other large-scale hydro-electric projects materializing.

Mr. H. Bentham: I gather from the paper that there may at times be some unreliability of the supply, and I should like to have some further information on this point. Looking at Fig. 1, I notice that in the North Island the current is consumed about 105 miles from its source of supply. I should be interested to know whether there have been any failures of the transmission system; if so, are such failures frequent, and what is their duration? I should also like to know whether any failures are due to lightning, and whether there is ever a shortage of water.

With regard to the question of wayleaves, in Great Britain it usually takes from 18 months to 2 years to get the necessary details settled. If that time could be reduced, quite apart from the cost of wayleaves, which is very high (and in regard to which, I understand, there is no trouble at all in New Zealand), it would help matters very much in this country.

In New Zealand the bulk-supply charge is roughly £8 per kW. Compared with the charges on the South-East England grid, this tariff is lower at 100 per cent load factor, but at load factors of 25 per cent the New Zealand tariff is 0·899d. per unit compared with 0·579d. for the grid; and we think the grid tariff extremely high. It is obvious that with a bulk-supply charge of £8 per kW it is necessary to introduce a tariff which will encourage very high load factors; otherwise the average price required would be exceptionally high. I assume that in New Zealand the necessary services are charged at a fairly high price and the remainder at an exceptionally low price—in fact, perhaps very little above cost; probably this is the reason why the load factor is so high. I understand there are 36 000 electric cookers in use in New Zealand. It seems to me that for the use of a 7-kW cooker one would have to pay a very high unit charge for it to be remunerative, despite the satisfactory diversity factor.

On page 72 it is stated: "The Government has not taken any steps to compel the closing-down of these plants, but has endeavoured to modify the standard supply rate to an extent sufficient to secure practically the whole of the load." I assume that this means that those generating stations are allowed to run which can generate at a lower price than that at which they can buy.

On the same page it is stated: "When the general system of supply becomes available it is perhaps reasonable that the capital which the owner has invested in these local plants should be protected. It is not, however, reasonable that this capital should be fully protected. . . ." That statement seems contradictory, and I should like to have some further explanation of it. The references to interruption under (*a*) and (*b*) on the same page rather suggest that the system is subject to a fair amount of interruption. If that is the case, the New Zealand method of working would not prosper if it were applied to this country.

Mr. W. McClelland: In presenting the paper Mr. Gauvain told us that before the Local Government Loans Board would authorize a loan for future extensions it was required that a revenue equal to 17 per cent of the capital cost of the extension proposed should be guaranteed. According to the curves shown in the paper, the capital expended per consumer at the present time is about £100, and the revenue about £10. So that for the present extensive supply system the ratio of revenue to capital is approximately 10 per cent. Out of this 10 per cent revenue, the authorities have paid all operating costs and interest on loans, and have allocated more than £1 000 000 to depreciation, sinking fund, reserves, and surplus. It seems to me to require some explanation why, for future extensions, a figure of 17 per cent for the ratio of revenue to capital should have to be guaranteed, when up to the present the figure of 10 per cent has given the excellent results shown in the paper.

Mr. A. H. D. Markwick (*communicated*): A family of curves showing equal gross or net revenue per consumer may be superposed on the curve given by the author in Fig. 12. These curves take the form of a family of rectangular hyperbolæ, as shown in Fig. B. It will be noticed that a reduction in average price per unit from 10d. to about 5d. actually reduces the revenue per consumer. As the average price per unit falls, however, this tendency is reversed, and the gross revenue per consumer increases quite rapidly. Reference to

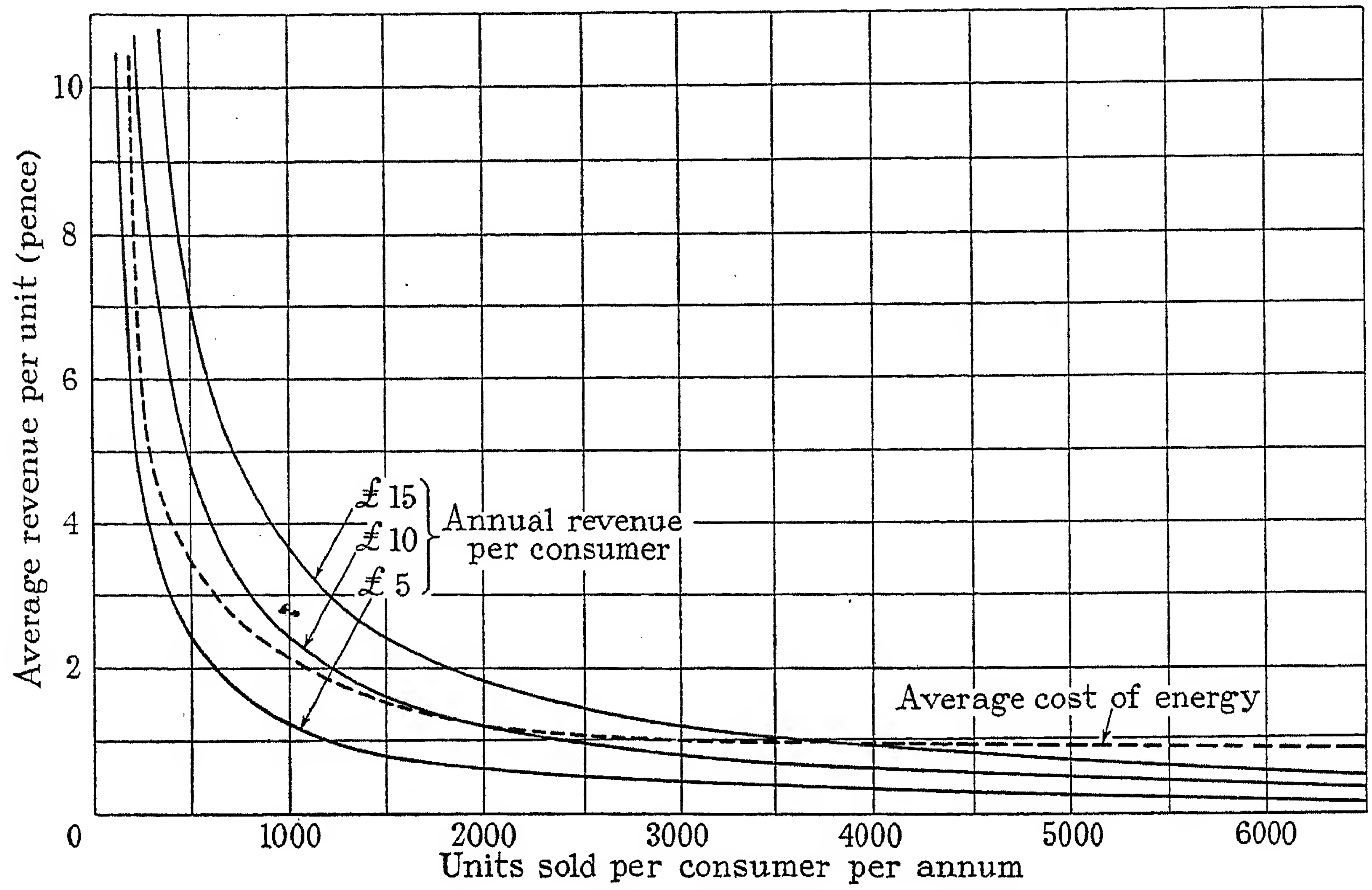


FIG. B.—Curve showing relation between cost of energy and units sold per consumer (average of 92 supply authorities in New Zealand for year ended 31st March, 1933). Curves showing equal revenue per consumer are superposed.

curves of this type given by Mr. J. M. Kennedy and Miss Noakes* shows that these are essentially similar to those given by the author. The tendency, when very high average prices are charged for current, for a reduction in tariff to be associated with a possible fall in total revenue, probably accounts for the reluctance of some of the smaller undertakings in this country to adopt a more progressive policy. The paper clearly demonstrates the shortsightedness of this view.

[The author's reply to this discussion will be found on page 86.]

North-Western Centre, at Manchester, 6th November, 1934.†

Mr. W. Fennell: The figures as to the units consumed by the people of New Zealand are really sensational. The author stated that the area of that country is about the same as that of Great Britain, but as a matter of fact it is 25 per cent larger. The population of New Zealand is about equal to those of Manchester, Salford, and Leeds, put together. To imagine the population of those three cities spread over the whole of Great Britain gives one an idea of the attenuation of the population of New Zealand. It is no small feat to have been able to get electricity installed by 97 or 98 per cent of the population. It would be interesting if the author could give further particulars of the tariffs. Energy is apparently sold in bulk to distributors per kW without any unit charge, but we are not told how the consumer buys it. Some of us have sold electricity retail at a fixed charge, without a meter. In the area served by the undertaking with which I am associated there is still a housing estate where the tenants pay a fixed weekly charge for electricity, and I believe that if the consumption per head of population were calculated for the housing estate it would be at least equal to that quoted for New Zealand. I should like to know why in New Zealand they should sell at a flat rate, in preference to adopting a 2-part tariff made up of a rateable-value or floor-space charge plus a unit charge.

Dealing with the earlier part of the paper, I am rather interested in the reference to the Telegraph Act of 1865, which was followed by the Electric Lines Act of 1884. It would be interesting if we could get an idea of the provisions contained in the latter (Lines) Act, so that they could be compared with those prevailing in this country. With regard to the Electric Power Boards and their organization, the paper states that the supply undertaking cannot raise money by loan to erect mains outside the Power Board district, although it can supply beyond that margin. One would have thought that to prevent the undertaking from borrowing money to develop the whole of its area would have handicapped rural development, but it does not seem to have had that effect, seeing that 98 per cent of the inhabitants are taking a supply.

On page 64 under Section B(4) it is stated: "any person liable to pay a rate under this section is also entitled to receive free of charge for use in his property, electricity equivalent in value to the amount of such rate paid in that year." This seems to be a splendid business-getting proposition, but I should imagine the British public hope it will not be applied in this country.

It is quite understandable (page 65) that the Boards

* *Journal I.E.E.*, 1933, vol. 73, p. 103.

† The paper was presented at the meeting by Mr. W. P. Gauvain, on behalf of the author.

should have to spend almost all their capital at once on the transmission system, and capitalize their interest for some years to come. Our C.E.B., of course, has to do the same thing. There is a hint that in New Zealand the purchasing authority is the Government, which appears to indicate a leaning towards complete nationalization.

I should like to ask how often wiremen are struck off the list. We have a similar problem in connection with the National Register in this country.

It would be useful if the New Zealand supply regulations could be published as an addendum to the paper, as a comparison with the British regulations. I should like to support what the author has said as to the wisdom of circulating new regulations for criticism before they are published.

The curve shown in Fig. 12 appears in a more understandable form than the similar one given 12 months ago by Mr. Kennedy and Miss Noakes. The difference between the two is that the New Zealand dots do seem to approximate to the line. The fact that electricity is purchased in bulk without any unit charge but with a kW charge may have had a considerable effect upon the New Zealand curve.

New Zealand appears to have already done what we are trying to do to-day, namely to get the farmer to use electricity for almost all purposes. I can see signs in my own area of similar figures to those given in the paper being obtained in some of the rather more remote rural areas where farmers have adopted electricity within the last 2 years. Until then they raised many objections to the presence of the poles which brought the supply near to them, but now they are becoming very keen on the availability of supply.

I should like to mention the fact that our grid tariffs follow the idea embodied in the New Zealand bulk-supply tariff, namely a fairly high kW charge. This has enabled a low unit charge to be chosen here. It allows the smallest undertaking to develop in a country area, because it allows of a very low unit charge on the 2-part retail tariff, and so induces the farmer to use electricity.

Mr. W. N. Y. King: We are informed by the author that in the country districts of New Zealand the price for cooking and heating is from 1d. to 1½d. per unit. The authorities in New Zealand are to be congratulated on achieving such a low figure.

Mr. W. E. Swale: I greatly admire the wonderful development work which has been done in New Zealand. In a period of a little over 10 years the annual consumption per head of the population has reached 452 units, which is almost as high as the figure we hope to reach in this country in the year 1940. The Power Boards have been able to proceed with their work untrammelled by vested interests. They have engaged in all kinds of interesting departures from preconceived ideas, and have been able to launch out on distribution schemes which in this country are not possible. What, by the way, is the value of the English pound sterling in New Zealand? It is also important to know something about the cost of competitive forms of fuel. Can the author give any idea of the average cost of fuel delivered at the house? Is there any competition with municipal gas companies, and what is the price of paraffin?

It is quite startling to read of bulk supplies being given exclusively on the basis of a fixed charge, and no running charge. Is this altogether sound, in view of possible future development? Are water supplies susceptible to seasonal variations, and do climatic conditions affect the load? I should imagine that, in New Zealand, temperatures are lower in the cold season than in this country, so that for electric building heating the peaks in the cold period will be greater than in England. Whereas the domestic load factor may reach the figure of 40 or 50 per cent, the industrial load factor is never likely to reach more than 15–20 per cent. With a 15 per cent load factor the industrialist would have to pay 1·4d. per unit, i.e. 15 per cent more than the bulk-supply charge per unit. Can the author give some information as to the conditions under which water heaters have been sold in New Zealand? Have unrestricted supplies for this purpose caused any embarrassment? A statement on page 64 interests me: "This particular method of rating has been used in one or two cases as a means of forcing ratepayers to become consumers of electricity." It would be delightful if we had something of the kind in this country. The remarks on page 72 under the heading "Charges for Bulk Supply" are very interesting. Apparently bulk supply has not been made compulsory; the owners of private power stations are still allowed to run them when they think fit, although the benefits are very doubtful. In effect this policy sanctions the principle of stand-by plant, which is fundamentally wrong.

With regard to the industrial load, what proportion of the total kWh sold is used for industry? Presumably there is not much manufacture, but large loads may be expected for dairy farming and for refrigeration at the terminal ports of the frozen-meat traffic.

Mr. C. L. E. Stewart: The most striking feature in the paper is the absolute reliance on water power, there being practically no stand-by or reserve plant driven by another form of energy. When I read the paper I had before me an atlas, and from this I gathered that the rainfall in New Zealand is very much heavier than in England, and is presumably seasonal. Is this so? New Zealand lies between latitudes 34° and 46° S.; if these latitudes were transferred to the northern hemisphere the lines would pass through Switzerland on the one hand and North Africa (Morocco and Algeria) on the other. The lighting-up time will therefore be later in the winter and earlier in the summer. Could the author give the times of sunset in Auckland (lat. 37° S.) on the longest and shortest days? I imagine that New Zealand loses an average of 1 hour's lighting units, from this cause, as compared with England. The climate in New Zealand must be warmer than in England; I imagine that there is not much frost or snow, except on very high ground.

I notice that there are some large lakes high up in South Island; at what height do these lakes stand, and are they commercially available for current generation when the demand for power necessitates plant extensions? Do the lakes and rivers in the higher regions become frozen up in winter? Fig. 2 indicates that the west side

of South Island is practically blank. I gather that the mountains are rather close to the coast, run very steeply down to the sea, and are forest-grown. The rivers which flow down these slopes appear to be suitable for supplying cheap power. The conditions look similar to those in Norway.

Apparently there are four coal districts in New Zealand; it would be interesting to know whether there is a sufficient quantity of good-quality coal for steam-raising and domestic purposes at a reasonable commercial price delivered to the consumer. If the coal is poor in quality, and difficult to get and deliver to the consumer, it makes a great difference to the value of electricity.

With regard to the gold mines, of which there seem to be four or five, do these take any big blocks of power which would bring up the average consumption per head of population to the high figure stated in the paper?

The kVA charge looks high, but I understand that each quarter stands absolutely on its own. With the Central Electricity Board the charge is yearly; which makes a great difference.

The capital cost of electricity supply in New Zealand must of necessity be higher than that in England, because I believe practically all the plant is imported from a great distance. Let us compare these apparently high charges with the corresponding figures for England. The Central Board's kW charge in this area is £3 7s. 6d., not to authorized undertakers, but to the favoured few. The remainder have to pay added charges for transmission lines. In the case of two small industrial towns less than 40 miles from Manchester that I have details of, the added charge is £4 6s. 11d. in one case and £3 9s. 0d. in the other case, making totals of £7 14s. 5d. and £6 16s. 6d. per kW respectively.

In each case the scale of charges in New Zealand works out at a less sum per annum than that of the C.E.B., plus the added charges.

I should like to know whether difficulties are encountered in connection with the ratepayers' meetings. In England, if powers are sought which might possibly result in a charge on the rates, there is great difficulty in getting the ratepayers to agree. What happens is that those who are in favour, or at least not against, the proposals, do not bother to attend, and those who are against attend in full force.

A word which occurs frequently in the paper is not in common use in this country; I refer to the word "reticulate." The dictionary gives to it the meaning "formed like, or resembling, a network"; it is therefore a very apt word as used in the paper.

I think everyone will be glad to note that local authorities in New Zealand are not allowed to obtain money from the electricity undertakings for the purpose of the rates. What seems to me to be a most ridiculous procedure, and one which is not uncommon in this country, is for a local authority to pass a resolution allocating, say, £20 000 to the relief of rates, and a later resolution giving instructions for application to be made for sanction to a loan of, say, £100 000 for extensions to the electricity undertaking.

Mr. T. W. Ross: It is interesting to hear how the New Zealand Government sell their electric power in bulk, and also of the high load factor. I imagine that a large percentage of the power must be used for agricultural or domestic purposes, and it is surprising that load factors of over 60 per cent are obtainable with this class of load. There must surely be some inducement to consumers to level out their demand in order that such load factors may be attained. It would be interesting to hear of the arrangements in force for the purpose of inducing consumers to keep a level demand, and also what tariffs are in use for different kinds of consumers.

Mr. W. Kidd: Will the author tell us what periods are allowed for the redemption of the capital costs of electricity supply in New Zealand?

The Author's Reply to the London and Manchester Discussions.

Mr. F. T. M. Kissel (*in reply*): I wish to thank members for the reception given to the paper, and, although approximately 12 000 miles distant, I hope that my replies correctly interpret the thoughts of those seeking further information. I should like also to thank Mr. Gauvain for agreeing to present the paper. He has been, during his residence in New Zealand, so intimately associated with much of the development that I felt sure the paper could not have been in better hands.

Regarding his inquiry as to whether, as the result of experience in the past few years, I still favour the system of having no unit charge, I would say that for wholesale supply to authorities taking the whole of their supply from the Government system I consider the present method of charging satisfactory. It may not be quite so satisfactory to the generating authority where the distributing authority owns and uses other generating plant for peak-reducing purposes, and in more recent contracts the plain maximum-demand wholesale rate has been offered only on condition that peak-reducing plants are not operated.

For the information of Mr. Coates, who is interested to know the reason for the apparently small honorarium paid to the chairman of a Power Board, I wish to say that these Boards now meet once a month for the formal transaction of business, and that now the Boards have finally decided upon their construction programmes the actual administration of affairs is in the hands of the Boards' executive officers. In some isolated cases the chairman of a Board gives his services free, and approximately 30 per cent of the chairmen act for less than £100 per annum.

Mr. Kerr is interested in the "availability" rating powers. Only two Power Boards have adopted "availability" rating, and it is not a very serious proportion of the aggregate amount collected as rates. Thus the figure for the year ending 31st March, 1934, was £1 378 out of a total of £67 873, which goes to show that "availability" rating has served its purpose and is not being utilized to any appreciable extent. The maximum amount that a ratepayer may be called upon to pay as "availability" rate in any one year is £30, and the minimum 10s. Power Boards pay the usual rates to the local municipal authority in whose area the Board's

premises happen to be situated, but it is not possible at the moment to quote any amount, either individual or aggregate, as requested by Mr. Kerr.

I am afraid that I have not sufficient knowledge of the conditions in England to assist him in finding a specific remedy to bring about better results. I might suggest, however, that such success as has been attained in New Zealand has been largely brought about by combining urban and rural areas, and by placing control of the distribution in the hands of authorities who have no avenue for absorption of profit other than the electric supply business. There is a movement in this Dominion for the setting-up of an organization which will be the counterpart of the Electrical Development Association in Great Britain, and its main function will be to launch intensive load-building campaigns.

Regarding the electrical wiring regulations, the Public Works Department, recognizing that the I.E.E. Wiring Regulations are more advisory than mandatory in nature, modifies where necessary any I.E.E. Regulation it may adopt as the basis of a similar regulation for New Zealand, where regulations are mandatory, and as a consequence the cost of wiring is not inordinately high in this country.

Mr. Wilson comments on the high load factor obtained in New Zealand. This is largely due to a high diversity factor between the large areas of country reticulation in combination with the urban areas. The milking peaks do not coincide with the industrial peak in the cities, and in most of the rural areas change-over switches have been installed in conjunction with the domestic hot-water system and the milking motor in the milking shed, or alternatively between the milking motor and the electric range. Domestic electric hot-water systems in the urban areas are controlled during peak periods either by time switches or by relays actuated by pilot wires. Cheap night rates are also in general use for domestic waterheating, and, taking all the above factors into consideration in conjunction with the quarterly maximum-demand system of charging for bulk supply, the high annual load factor is the result. The proportion of urban to rural consumers is approximately 214 000 to 120 000.

Mr. Wilson is correct in assuming that the high proportion of wooden buildings in this Dominion is to a large extent responsible for the grade of wiring work insisted upon. The fire risk would be a serious one if inferior materials and workmanship were permitted. Each electric supply authority is bound by law to make a periodical inspection of each consumer's installation to see that no electrical hazards exist; the maximum time between inspections must not exceed 5 years.

Mr. Bentham asks whether transmission-line failures are frequent, and I am pleased to be able to inform him that such interruptions are very few and far between, the main transmission lines in most instances consisting of more than one circuit. For the 12 months ending 31st March, 1934, the interruptions to the three principal cities supplied from the Government schemes were as follows:—

Auckland from Penrose substation.—One of 11 minutes and one of 8 minutes, in each case due to the failure of a 110-kV pillar insulator on the high-tension busbars at Arapuni. Total, 2. Duration, 19 minutes.

Wellington from Khandallah substation.—One of 18 minutes due to a broken jumper and mechanical failure of 110-kV air-break switch at Khandallah. One of 1 minute due to lightning flashover on transmission line. One of 4 minutes due to accidental earthing of 11-kV oil circuit-breaker at Khandallah. One of 3 minutes due to cable fault on customer's cable system and inadequacy of relay system. Total, 4. Duration, 26 minutes.

Christchurch from Addington substation.—No interruptions.

An examination of the above details indicates that, with the exception of one interruption of 1 minute at Wellington, the whole of the interruptions were such as might have occurred even if there had been no long transmission lines, and if the power stations had been located close to the load centres. The efficiency of transmission has been greatly improved in recent years by systematic maintenance and by the periodic testing of insulators by live-line methods. Any units found defective are removed at the first opportunity. Live-line methods of insulator changing and even of pole and cross-arm changing are used wherever it is not possible to put lines out of commission for repair. Lightning does not cause much trouble on the e.h.t. lines in New Zealand. As regards shortage of water, in the past there have been isolated instances of brief duration during which stand-by steam and Diesel plants have supplied the deficiency and ensured continuity of supply.

Regarding Mr. Bentham's comment on the retail rates for electric ranges, 1d. per unit is fairly general for this class of load, and this is apparently a profitable figure. In the larger cities ¾d. per unit is a common rate. His assumption anent generating stations being allowed to continue in operation if the generating costs are cheaper than bulk-supply rates is correct. He mentions protection of capital invested in such plants at the time when the Government supply becomes available, and assumes there is a contradiction as regards the meaning of "protection." The point is that the owners of these plants cannot have it both ways. If Government supply is available and a contract has been signed to take such supply, the price per kVA may be made more favourable to the owner provided the plant is shut down completely, but if the owner still desires to use the plant during peak hours, as mentioned in paragraph (*e*), page 72, the terms of the contract will naturally not be the same as in the former case.

Mr. McClelland raises the question of 17 per cent guaranteed revenue. This requirement has since been lowered, but originally the revenue required to cover all charges was computed on the following basis: interest, 6 per cent; sinking fund and depreciation, 4 per cent; cost of power, 5 per cent; maintenance and patrol, 2 per cent.

Mr. Markwick's contribution to the discussion is of interest, and the curve accompanying his remarks is appreciated.

Mr. Fennell asks why electricity is sold in New Zealand at a flat rate; such is not the case. The Public Works Department functions only on the wholesale side of the selling business, and its method of charging for bulk supply is explained in the paper. The retail side of the business is handled by Power Boards and other local

authorities in the electric supply business. The schedules for retail supply vary somewhat in different districts, and in the majority of cases separate tariffs are designed for lighting, heating, and power respectively. As a general rule, the tariffs are so framed that the average price per unit decreases with increased consumption. Tariffs based on rateable values are unknown in New Zealand.

Regarding expenditure of loan monies in Power Board districts, it may help Mr. Fennell to understand the position better if a specific example be cited. An electric-power district (which may or may not have an " outer " area incorporated in its constitution) covers 2 620 square miles, of which 1 648 square miles is " inner " area with a population of 52 000 and 972 square miles is " outer " area with a population of 3 000. The loan proposals are submitted only to the ratepayers of the " inner " area, whose properties are pledged as security for the loans. If the ratepayers in the " outer " area desire an electric supply they can obtain it by going through a prescribed legal process, and in this way they become absorbed into the original " inner " area. On completion of this merging of territory a separate loan proposal to reticulate the newly added area is submitted to the ratepayers, whose properties in that area will be pledged as security for the loan if carried. The alternative is for a Power Board to extend its lines beyond the boundaries of its " inner " area, the cost of such lines being paid out of accumulated profits as distinct from loan money, which cannot be legally spent beyond the boundaries of the area pledging the security. In the course of time the gradual absorption of the " outer " area into the " inner " area will take place just as quickly as the financial prospects warrant it.

In reply to Mr. Fennell's query regarding the Electric Lines Act, 1884, this Act contained 68 sections dealing with the construction and regulation of lines for telegraph and telephone purposes, and for electric lighting purposes. Power was given to make regulations for the public safety and for the removal of dangerous lines. This Act was administered by the Commissioner of Telegraphs, and in 1911 the Public Works Act was amended to provide for transferring the administration of electric lines for lighting, heating, and power purposes, to the Minister of Public Works. It is regretted that the large number of sections contained in the 1884 Act preclude the possibility of reducing them to a concise summary suitable for inclusion in this reply.

Regarding the Wiremen's Registration Act, the principal grounds for removal of names from the register are as follows: (1) Seriously defective work. (2) Two or more endorsements for defective work. (3) Imprisonment. (4) Improper conduct. Since the Act came into force, three names have been removed under heading (1) and four under heading (3). Every 5 years the register is purged, after every wireman whose name appears in the register has been circularized; and if a wireman does not reply within the specified time, stating that he wishes his name retained on the register, his name disappears therefrom. The names so treated total 200 to date.

In reply to Mr. Swale, the English pound sterling is worth 25s. in New Zealand currency. The average retail prices in New Zealand for the competitive fuels mentioned by him are: paraffin, 2s. per gallon; gas, 3s. 6d. to 10s. 6d. per 1 000 cub. ft.; domestic coal, 35s. to 60s. per ton.

Electric water heaters are purchased by the consumer, but there is no uniformity in the method of charging for electricity used. Some supply authorities permit up to 22 hours' service with time switches to cut off the heaters during the peak hours. Cylinders of 25–30-gallon capacity are fitted with 500- or 750-watt elements for the long-hour service, and an average charge is £1 per annum per 100 watts. Where continuous service is available, the annual charge ranges from £12 to £15 per kW. Other rates in use are: $\frac{1}{3}$d. per unit between 10 p.m. and 7.30 a.m., $\frac{1}{2}$d. per unit on time-switch limiting the service to 18 hours, $\frac{1}{2}$d. per unit on change-over switch with electric range, and $\frac{3}{8}$d. per unit if thermostat and time-switch installed. The large number of time switches in use effectively remove the water-heating load during peak-load periods, otherwise embarrassment would result, as mentioned by Mr. Swale.

It is not easy to give Mr. Swale exact figures showing the proportion of units used for industrial purposes, but an approximate value for the year ending 31st March, 1934, appears to be in the vicinity of 252 millions, as against 416 millions for other purposes.

In reply to Mr. Stewart, the rainfall in New Zealand varies from about 10 in. at Alexandra in Central Otago to a maximum of 300 in. 100 miles farther west. The intensity and distribution of rainfall is mainly determined by the mountain ranges, and is particularly high where these face the west and correspondingly low where they face the east. Where not influenced by mountain ranges, the rainfall varies between 40 and 50 in. Rainfall is generally well distributed, but there is a definite predominance in the period July–December. The snow-fed rivers of the Southern Alps, however, usually run high from September to May. The summer climate in New Zealand is not very different from that in England, but the winter climate is much warmer. Night frosts are common, but snow and ice are rare in the low country.

The lakes in the South Island are generally available for current generation, Te Anau and Manapouri by diversion to the sea. The leading particulars of these lakes from north to south are:—

Lake	Area	Height above sea level	Mean flow
	square miles	ft.	cusecs.
Coleridge	14	1 672	580
Tekapo	34	2 321	3 150
Pukaki	31	1 588	5 350
Ohau	24	1 720	2 350
Hawea	45	1 062	2 170
Wanaka	76	928	5 640
Wakatipu	110	1 069	5 740
Ta Anau	138	694	9 750
Manapouri ..	56	597	4 180
Monowai	10·5	670	500

Ice is never likely to give serious trouble in any of the lake schemes. Tekapo, only, makes ice in a very exceptional season.

The west coast of the South Island carries a comparatively small population, and is largely forest-clad. The rivers are generally unsuitable for power production, on account of the large amount of greywacke shingle carried.

The times of sunset in Auckland on the longest and shortest days are 7.14 p.m. and 4.41 p.m. respectively.

Good-quality coal for steam-raising and domestic purposes is available in sufficient quantities without the necessity for importing supplies.

Regarding average consumption *per capita* per annum, the gold-mining loads do not make an appreciable difference. The overall figure for the year ending 31st March, 1934, was 472 units, and after deducting gold-mining and traction units the resulting figure was 430.

Mr. Stewart's assumption regarding the use of electricity profits for the relief of rates is not strictly correct, as, although Power Boards are prevented from so doing, it is still permissible for municipal councils to appropriate electricity funds for the above purpose.

Mr. Ross's questions are mainly covered by my replies to Messrs. Wilson, Swale, and Fennell.

For the information of Mr. Kidd, the redemption period of capital expenditure is generally fixed at 36½ years, for expenditure by the Government and the earlier power supply authorities, although latterly there has been a tendency to reduce this period to about 25 years where the assets consist solely of distribution lines.

THE BREAKDOWN MECHANISM OF IMPREGNATED PAPER CABLES.

By D. M. ROBINSON, Ph.D., M.S., Associate Member.

(*Paper first received* 18*th July, and in final form* 29*th November*, 1934; *read before the* TRANSMISSION SECTION 20*th February*, 1935.)

SUMMARY.

A new technique of cable examination has been developed. Incipient faults have been studied before actual breakdown with the aid of a microscope, the papers having been freed from oil and dyed to show up the waxing. The types of waxing observed are classified, and their part in breakdown is discussed. The deterioration is always found to be in connection with the conductor, generally through the gap of the first paper. The occurrence of the maximum deterioration at a distance from the conductor is explained, and a diagram showing the path of failure in an actual case is given.

The conclusion reached is that failure originates from the ionization in a void in contact with the conductor, but that subsequent breakdown takes place by carbonization of the compound. Such carbonization requires time for its completion and is the chief factor in the voltage/time-to-breakdown curve. It takes place both longitudinally, over the surface of the paper, and perpendicularly through it.

The results obtained in the laboratory are compared with those in service, and the types of failure are described.

The effect of d.c. stress on cables is discussed and the advantages of routine d.c. testing of feeders are explained on this basis.

CONTENTS.

(1) INTRODUCTION.

The examination of cable after failure, in service or in the testing laboratory, can give little clue to the mechanism of breakdown, since the energy present in the final arc burns out the traces of the deterioration giving rise to failure.

It is possible, however, from the indications of thermometers or thermo-couples located on the cable sheath, or alternatively from the measurements of dielectric power factor obtained with the Schering bridge, to stop a laboratory test before actual breakdown takes place, and thus to preserve the whole of the evidence.

The author's colleague, Mr. G. M. Hamilton, has made the examination of the individual paper tapes of impregnated cables especially illuminating by developing the magenta wax test. This test depends on the insolubility of cable wax* in the usual organic solvents,† and the fact that paper protected by wax will not "take" a water-soluble dye. (Magenta dye has been chosen because of the contrast given in photographic work.)

The result is that impregnated papers subjected to extraction and dyeing bear conclusive evidence of any waxing which has been produced upon them, even when the deposit is much lighter than any which could be seen on the impregnated paper before treatment.

All the cables dealt with are of the type in which the dielectric consists of paper tapes about 1 in. wide lapped helically on to a stranded copper conductor, the whole being dried and evacuated at 120° C. for upwards of 100 hours, with the tank pressure normally maintained below 1 mm of mercury during the final period. The hot impregnating compound, which consists of a paraffin-base oil with about 23 per cent of resin, is admitted without breaking the vacuum.

The work herein described has been chiefly concerned with 66-kV single-core cables of modern manufacture, with the papers "gapped"; that is to say a given paper does not "overlap" itself, but is so wound that a "gap" of about $\frac{1}{16}$ in. is left between its adjacent edges. Successive papers "overlay" one another in such a manner as to give the longest possible leakage path from gap to gap in each direction. This is the so-called 50 : 50 overlay, in which the centre of the second paper lies exactly over the gap formed by the first paper, and so on.‡ The direction of lay is normally, though not invariably, reversed every 6 papers. All the single-core cables discussed were provided with a final layer of punched metallized paper and were lead-sheathed in the normal manner. Both oval and circular conductors were used in the tests.

Many modifications in construction, manufacture, and treatment, have been tried, and the effects of some of these are described.

(2) TYPES OF WAXING.

Examination of the dyed papers from cables after withdrawal from service or following laboratory tests has shown that there are certain well-defined types of

* No historical summary of previous work has been made. Instead a chronological bibliography with appended notes is given.

* Wax in cables is produced by the condensation of the hydrocarbons forming the impregnating oil. Formerly it was known to cable engineers as "X" and "cheese," but since it has been shown by Clark and Mrgudich [see Bibliography, (6)] to be similar in constitution to paraffin wax the term "wax" has been used throughout this paper.

† See Bibliography, (1).

‡ Cables with different overlay (e.g. 60 % : 40 %) and cables in which each paper overlaps itself have also been examined.

waxing. These have been designated as follows, typical examples being shown in Fig. 4 (see Plate 1, facing page 96).

*Void Waxing.**

This occurs at random in any part of the dielectric, is quite irregular in shape and area, and is free from all carbonization and treeing.

Gap Waxing.

This occurs at the upper and lower boundaries of the helical space or "gap" formed between successive turns of a given paper tape. It, also, is free from carbonization. It is really a special case of void waxing, but is classed separately because it often occurs alone.

Strand Waxing.

This occurs only near the conductor as a result of the stranded shape of the latter, and the corresponding variations of stress. It is a maximum at the crest of the strand.

Strand Space Waxing.

This occurs in general only on the conductor side of the conductor paper between two strands, waxing at the crests of the strands being absent on account of the perfect contact between paper and copper.

Bush Waxing.

This comprises any waxing which occurs in association with carbon, even when only microscopic deposits of the latter are present. The type receives the name because it frequently consists of a waxed area with small fronds or streamers at its edges. Due to local conditions, it may take up the form of any of the first three types, but may always be distinguished from them by its distribution, origin, and the presence of carbon.

(3) The Significance of Wax in Cable.

The cables examined by the new post-mortem technique included:—

(*a*) Samples removed from both sound and faulty feeders after many years of service.

(*b*) Full drum lengths after stability test for periods varying from 1 month to 2 years.

(*c*) Short lengths subjected, for periods from 7 to 50 days, to daily heat cycles in conjunction with moderate over-stressing.

(*d*) Short lengths overstressed without the application of loading current, i.e. voltage/time-to-breakdown samples (life 10–400 hours).

(*e*) Samples subjected to d.c. stress only.

(*f*) Unstressed samples after standing for upwards of one year.

(*g*) Unstressed samples as received from the factory.

The conclusions are:—

(i) Waxing in a given region, however slight, is evidence of gaseous ionization at that point during some part of the life of the cable.

* In this paper the term "void" is used to denote any gas or vacuous space in the stressed region of the cable.

(ii) On the other hand it is possible for gaseous ionization in a mild form to exist for several hours without forming enough wax to be detectable by the magenta wax test.

(iii) Waxing may be found in any part of a cable which has at any time been under sufficient stress.

The deposits are heaviest where:—

(*a*) The stress is greatest.
(*b*) The gas pockets or voids have the greatest thickness in the direction of the electric stress.
(*c*) The gas pressure has been lowest.
(*d*) The bombardment has been of longest duration.

(iv) Heavy waxing may occur in patches isolated from any other deposits. In well-manufactured cable which has undergone a number of severe heat cycles with constantly applied stress equivalent to, say, twice working voltage, the middle 25 per cent of the dielectric may be found heavily waxed, while the remainder is entirely free.

(v) In single-core cable no carbon is ever found in conjunction with wax occurring isolated within the dielectric wall.

(vi) Cables can and do operate successfully when so thoroughly waxed throughout that no free oil remains.

(vii) Well-manufactured "homogeneous" cable may break down without the preliminary formation of wax; alternatively wax may be formed only in the immediate neighbourhood of the failure.

(viii) No waxing is caused by the application of d.c. stress to cables containing voids, at any rate up to 1 000 kV per cm.

(ix) No waxing is found in unstressed cables, either as received from the factory or after standing for long periods.

(4) Arrested Breakdowns.

The work now to be described is based in the first instance on experience gained from over-voltage testing of single-core cables in the laboratory with about three to four times working voltage applied for periods varying from 10 to 400 hours.

On dissecting, in the usual manner, such a cable after it has shown a hot spot and been arrested before breakdown, the following observations may be made:—

(i) Under the sheath or metallized paper the dielectric is unaffected and remains so throughout the first 60 per cent or more of the dielectric wall.

(ii) As the unwrapping is continued a dry region appears, frequently accompanied by small spots of carbon in the gaps. A few papers farther down heavy treeing is found, and changes its longitudinal position systematically as successive layers of paper are removed.

(iii) The severity and scope of the treeing decrease as the conductor is approached, the last few papers appearing to be untouched in many cases.

To examine such treeing accurately, and to permit microscope work on individual papers, it is necessary to extract the compound or oil. The carbonization then shows up clearly, but waxing is only visible if severe. Since the waxing is often a valuable "background" of

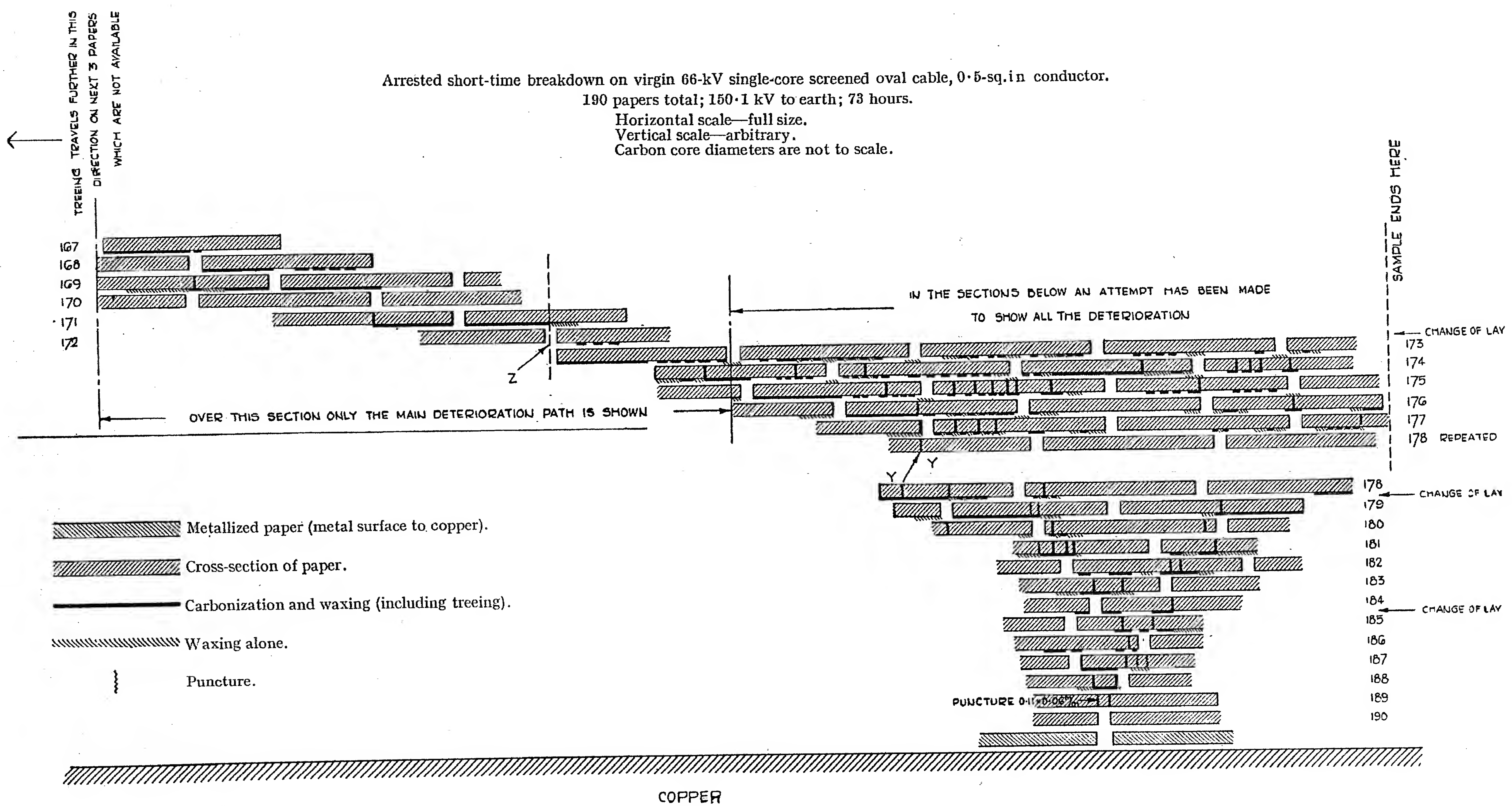


Fig. 1.—Mechanism of cable failure.

Note:—Only the carbon actually found on the extracted papers is represented. Any loose carbon occurring in the gaps is necessarily neglected.

Remarks.

1. Within the confines of one group of 6 papers the main tree travels perpendicularly to the paper edges and papers are therefore represented in full section.
2. The spread of deterioration parallel to the paper edge is never more than about half the conductor radius, and has to be ignored.
3. At the change of lay 179–178, the point Y has been chosen as reference, and examination of outer papers proceeds from this datum.
4. At the change of lay 173–172, Z is the point of reference, and only main deterioration is considered in the outer papers.

the carbonization in the examination of the cable, it is desirable in all cases to dye the papers and thus make visible every trace of wax. The papers are individually marked and numbered as they are removed from the cable, and after dyeing are re-located as described in the Appendix.

A large number of "failures" arrested in various stages of development have been examined in detail in this manner.

(5) DETAILED EXAMINATION OF ARRESTED BREAKDOWNS.

The maximum treeing and carbonization occur at a distance from the conductor, and on superficial examination it is not apparent that there is any conducting path between this carbon and the copper. With the aid of a microscope, however, it is possible to find a carbonized track in connection both with the treeing and with the gap of the first paper on the conductor, the latter termination of the track corresponding in general to some point of high stress on the conductor, e.g. the crest of a strand, a punch hole in the metallized conductor screen, etc. side. When the paper is dyed, this is particularly easy to see, as the dye penetrates only a fraction of the way from each surface. It is thus possible to scrape through the upper dyed region, and then through the central undyed portion till the first dyed fibres of the opposite surface are picked up. Apart from the surface scabs or tracks, the thread or core of black maintains a fairly uniform diameter of the order 0·05 to 0·2 mm. The former value is representative in the early stages and near the conductor.

This "core" of black is not in any way weak mechanically, and it is certainly not merely the carbonaceous filling of a puncture. It appears, indeed, that the cellulose fibres are relatively unaffected, the core being more of the nature of a deposit in the interstices of the paper matrix. There is no impression of burning—i.e. there is no ash of any kind—the carbon is dead black, while the fibres around it show no evidence of scorching, the cross-section of the core having a very definite boundary.

While the upper termination of the deposit is, as already mentioned, a scab, at the most 0·5 mm diameter,

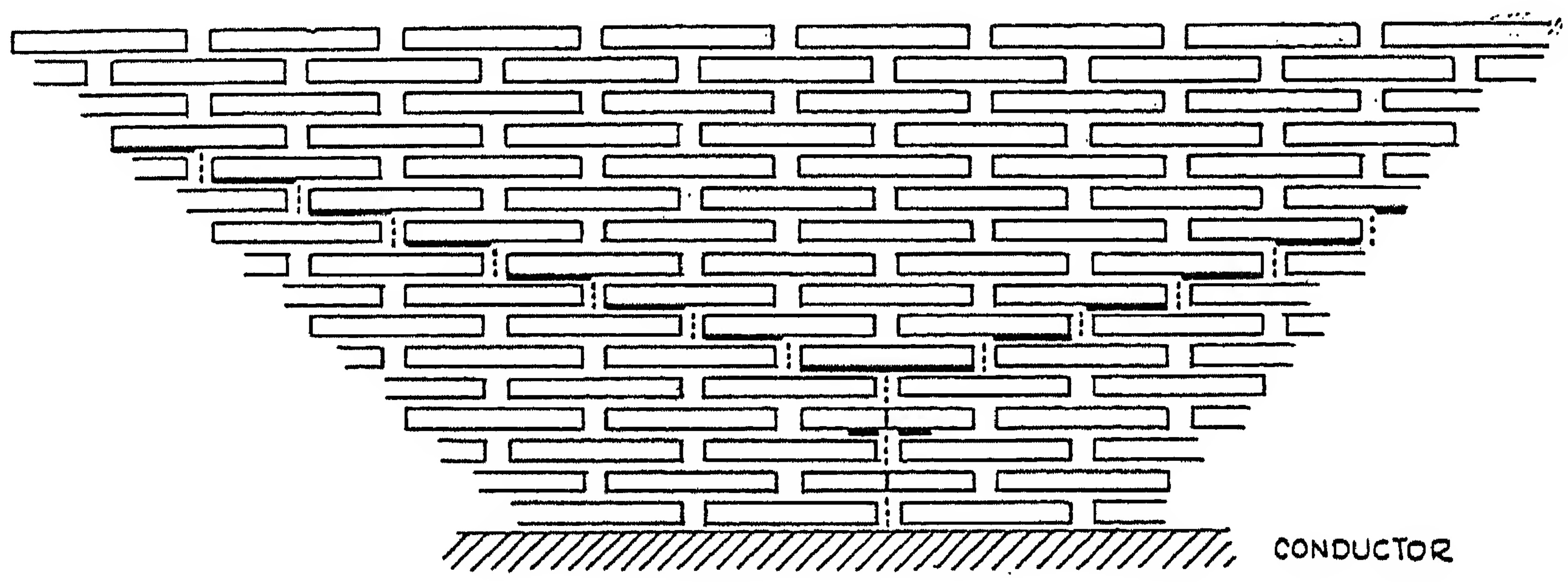


FIG. 2.—Mechanism of cable failure. Simplified case; 50 : 50 overlay.

The only breaks which occur in this carbon track are those caused by the paper gaps which lie in its path.

Examining the papers individually:—

The conductor paper normally shows no burning, treeing, or carbon deposits, until cable breakdown has actually taken place. No pinholes have been found.

The second paper from the conductor frequently appears entirely clear, or it may have slight gap waxing, arising from the gap in the first paper, but if it is examined just below any pock-marks or bush waxing on the paper immediately above* it, the microscope will reveal either a minute pucture or, more generally, a brownish-black fleck on the upper side. This is large enough to be seen with the naked eye when the paper is carefully examined, but is usually small enough to be missed or ignored in ordinary cable examination.

The brownish-black fleck can usually be scraped off, giving the impression that it is merely surface deterioration. Under the microscope, however, the fleck is seen to be a scab covering a much smaller spot of intense black. On teasing apart the paper in this region it is quite clear that the blackness extends through the paper and connects up with a minute pock-mark on the lower

* For ease of description the track is supposed to grow *upwards* from the conductor as represented in Figs. 1 and 2, and the terms "above," "below," "upper," "lower," etc., refer to such a case. In reality such a track may grow outwards from conductor to sheath in any direction.

the paper above it has on its lower surface a larger, blacker mark, showing already a tendency to tree formation, although only 1 or 2 mm long. This minute tree has its origin immediately above the deposit in the second paper from the conductor, and if that deposit occurs just below a gap in the third paper the tree will form on the fourth; otherwise it will form on the third paper.

This small tree may easily be scraped off the paper, which then may or may not show a small pock-mark. Microscopic examination of the top of the paper shows whether penetration has taken place. A number of cores may be found, very similar to that already described. Four of five is generally the limit in a region 3 or 4 mm square, but in general only one or two of these penetrations proceed farther. If part of the tree is below a gap in the paper above, this is the preferred region for "coring."

The trees on successive papers gradually become larger until they are long enough to bridge from one gap to the next above across the intervening half-inch or so of paper surface, and from this point outwards the main track is found to consist of a series of trees on successive paper tapes joined to each other through the gaps. This "step" mechanism is clearly seen in Fig. 1 (papers 176 to 167), while Fig. 2 is an idealized typical example.

In general, the main tracking extends longitudinally

in each direction. Part of the region between the two branches also contains smaller trees, and numerous cores originating from the branches of the main treeing. This secondary deterioration has been omitted from the idealized example (Fig. 2).

Still farther from the conductor the trees reach their maximum extent, penetration from the branches continuing for a few papers, and then deterioration stops relatively suddenly.

The treeing is a deposit on the surface of the paper and does not affect the paper fibres until a very advanced stage. In the solid-type cable this deposit occurs only on the paper surfaces facing the direction from which the track is coming. Treeing and coring are always accompanied by waxing, however far out from the conductor they proceed. The wax formed near the conductor is generally limited to the gaps, and may be so little as to be invisible to the naked eye. On papers showing treeing the "bush waxing" is always present over a greater area than the treeing; and is well developed when the tree is just beginning.

Systems of tracking of this type have been found in all stages from the conductor-gap core with the first small scab above it, to the advanced deterioration such as that represented in Fig. 1. No case of carbon occurring isolated within the dielectric, e.g. as a result of severe inter-layer ionization, has yet been found in the single-core cable.

(6) Effect of Special Conditions.

A. The application of gas pressure to the ends of an impregnated cable while under test results in a change of character of the deterioration. Fig. 5 (see Plate 1) shows the treeing obtained in such cables at 200 lb. per sq. in. in nitrogen, while Fig. 6 (Plate 2) shows for comparison the treeing obtained in the same type of cable at atmospheric pressure. The application of pressure clearly results in greater brilliancy and definition of the carbon tracks, but at the same time limits the waxing to the immediate vicinity of these tracks. Particularly in the finer examples from pressure cable [e.g. H, Fig. 5 (Plate 1)] it can be seen that the waxing only penetrates a certain distance from the track (about 1 mm), whereas under atmospheric pressure the bush-waxing fills the whole area around the advancing track.

B. When the papers near the conductor of an ordinary solid-type cable are applied with an overlap instead of a gap the appearance of the deterioration is somewhat modified.

The first stage is usually strand-waxing between the first and second papers from the conductor, arising in any void which happens to exist there, or is formed during the test. This strand waxing is exactly like the example in Fig. 4 (see Plate 1) and is followed by coring in many places from near the crest of the strand. Occasionally when the length tested happens to contain no such void, coring appears to commence direct from near the crest of the strand. After the first few papers the breakdown is scarcely distinguishable from that in a gapped cable.

C. If the maximum stress locally at the lead sheath is for any reason greater than that at the conductor, the treeing mechanism commences at the sheath and works inwards towards the conductor, and the treeing takes place on the paper surfaces facing the sheath, i.e. again facing the direction from which the track is coming.

This condition can be observed in the case of a cable with thin dielectric (0·1-in. wall) in which the stress at the conductor is diminished by sheathing the strand with lead. By smoothing out the stress irregularities at the strand an improvement of about 16 per cent is obtained in long-time breakdown voltage, but then the stress irregularities at the edges and perforation of the metallized paper ("H" paper) come into play, and the treeing starts its journey inward as described.

D. A more familiar case of the same sort occurs at points where the metallized paper is terminated in sealing ends or joints. If the stress-cone design is poor, or a small rough edge of metal is left at the base of the cone, the same type of treeing mechanism progresses from this point away from the metallized section of the cable. Usually this track steps down towards the conductor at each gap in the way already described for the true cable failures.

E. When heat cycles are applied to any solid-type cable there is always the danger that, on the cooling cycle, low-pressure voids will be formed. By dyeing the papers the location of such "breaks" in the compound column are clearly shown. The waxing is more severe than in a space produced by drainage, where the pressure is atmospheric, but there is no evidence that ionization at a distance from the conductor has any influence on the eventual breakdown of the cable by the mechanism herein described.

F. Samples of cable subjected to high-frequency voltage tests (250 000 cycles) show very much heavier waxing than those tested at commercial frequencies.

(7) Summary of Experimental Evidence.

Before proceeding to the theory of breakdown it will be well to summarize briefly the relevant experimental facts as follows:—

In impregnated cable deteriorating under a.c. stress:—

A. Carbonization starts from the conductor and "grows" outwards, choosing as origin any point of high stress on the latter. No carbon has been found isolated within the dielectric of a single-core or "H" type cable.

B. The gaps between papers are electrically weaker than the papers themselves, even when full of compound.

C. Carbonization of the treeing variety is always accompanied by waxing, but not vice versa.

D. The treeing normally takes place on the paper surfaces facing the direction from which the track progresses.

E. The maximum apparent deterioration occurs at a distance from the conductor.

F. The a.c. breakdown voltage is increased by:—

(*a*) Smoothing the conductor.
(*b*) Overlapping the papers.
(*c*) Increasing the pressure by gas or oil.
(*d*) Decreasing the porosity of the paper near the conductor.

G. The a.c. breakdown voltage is lowered by heat cycles, but only when the test voltage is applied during

the cooling cycle, the effect being accentuated when supply of air or oil is prevented.

H. Audio- or high-frequency discharge components can be detected in the charging current of all solid-type cables at a sufficiently high voltage. The magnitude of this discharge is greatest during the cooling cycle when the pressure is low, and is decreased by increase of pressure.*

J. When void formation is prevented by any means, e.g. the oil-filled cable:—

(*a*) The voltage/time-to-breakdown curve becomes flat after 3 or 4 hours.
(*b*) There is no formation of wax.
(*c*) No discharge can be detected.

K. The impulse breakdown voltage of impregnated cable is not affected by pressure.†

(8) Theory of Breakdown.

Consideration of all the experimental evidence leads to the conclusion that the type of breakdown considered commences with ionization of a gas space in contact with either the conductor or the sheath.

The impregnated paper consists of a matrix of fibres having the interstices filled with impregnating compound. The ionic bombardment at the electrode results in time in the disturbance of this impregnated barrier, the liquid being partly pushed out and partly condensed into heavier molecules with liberation of more gas. If the bombardment is sufficiently concentrated a path will eventually be driven through between the individual fibres of the paper matrix.

As a result of special methods of testing (to be described in a further communication) it has been proved that when the ionizing stream first penetrates a given paper there is no core of carbon visible in the microscope. Some time (minutes or hours according to severity) is generally necessary before sufficient carbon is accumulated to be distinguishable as a core.

During this period, however, the spark continues to flash through the embryo core. This spark now extends from the conductor through one paper to the lower surface of the third or fourth paper, its potential throughout being almost that of the conductor. The papers of the dielectric have, however, potentials corresponding to their position in the wall. Thus between the ionized column and each paper with which it comes in contact there exists a potential difference, the value of which increases with the distance of the paper considered from the conductor.

The tangential stress thus arising results in a surface discharge leading to condensation (with formation of wax), and finally carbonization of the compound in that random way which we call "treeing." This carbonization occurs in the "preferred tracks" of the spark. No trace is left on the upper surfaces of the papers in the early stages, because the track, being at conductor potential, is repelled from the copper and thus attacks the film of compound on the under surfaces.

The increase in the length and severity of the trees as the track proceeds outwards is due to the increasing tangential stress, the mechanism consisting more and more of the tree-gap-tree type as the track advances. For a given stress, breakdown across a surface takes place more quickly than through the paper, because in the former the barrier action of the paper fibres is absent and the electron bombardment is able to sweep before it the film of excess compound between paper surfaces, thus leaving the space free for ionization and tracking.

Let V_c be the potential of the conductor at a given time, V_p the normal potential of the paper under consideration, and e the voltage-drop along the track up to the paper considered. Then the tangential stress $S_t = K(V_c - V_p - e)$.

The further mechanism of deterioration now depends on the voltage-drop e.

Case I. If the voltage-drop is negligible the track is everywhere substantially at conductor potential.

Case II. On the other hand e may be small initially but rise as the trees develop and the current to be passed through this column increases. The rate at which new trees can be formed and penetration to new layers can take place then becomes dependent on the rate at which the main column can be burnt down to a lower resistance.

For Case I it is apparent why the dielectric between the copper and the overhanging branches of the track is undeteriorated (see Fig. 1). The track, being almost at conductor potential, shields the dielectric of this region from stress. In the crutch between the two main branches of the track the dielectric is still subjected to stress, which is no longer uniform or purely radial. There is tangential stress but it does not lead to the formation of long directional trees like those of the two main branches, because the current per layer to be supplied by the track is limited to that required by a small area of paper. The difference in the character of the deterioration is indicated in Fig. 1, the carbonization in the crutch being patchy. On the papers themselves this difference is very obvious.

For Case II, the whole system of the developing fault at any given moment is that of a transmission line having distributed resistance and distributed leakage.

The curve PQR (Fig. 3) shows V_p as a function of the distance from the conductor for a 0·5-sq. in. 66-kV circular cable with screened conductor.

In the early stages, when the track has first penetrated and the current through it is small, the voltage along it may be represented by PM. (For simplification of theory and drawings the dielectric has been assumed to consist of a few very thick papers.) The length of the ordinate between PM and PQR at any point represents the tangential voltage acting. These tangential voltages cause treeing on each surface in amount dependent on the voltage and the time for which it acts. The current taken through the main track to supply the branches results in a drop of voltage along the path (curve PST). Meanwhile the sideways travel has given the track further chance to go ahead, as shown by TUW. This results in the production of further tangential voltages. For each paper the process of treeing continues until the voltage of the outer carbon fronds at that paper has been brought down so near to the normal value

* See Bibliography, (18).

† *Ibid.*, (19).

according to position that the available tangential stress is below that required to cause treeing.

From the observed character of the deterioration it is difficult to say whether Case I or Case II is the better approximation to the truth, the only guide being the shielding effect of the "branches," which indicates that these have a potential very different from that of the papers through which they pass.

Actual tests on a tree system at a stress of about 150 kV/cm, in which good contact was made with the carbon track by means of mercury, showed it to have an equivalent resistance of 125 000 ohms through 17 papers with about 100 mA flowing. From this it can be shown that during the penetration process the drop along the main track is small in comparison with the test voltage and remains so until the carbon chain actually stretches from the copper to the sheath.

It is very likely that during the progress of deterioration the major drop occurs in the outer fronds or just

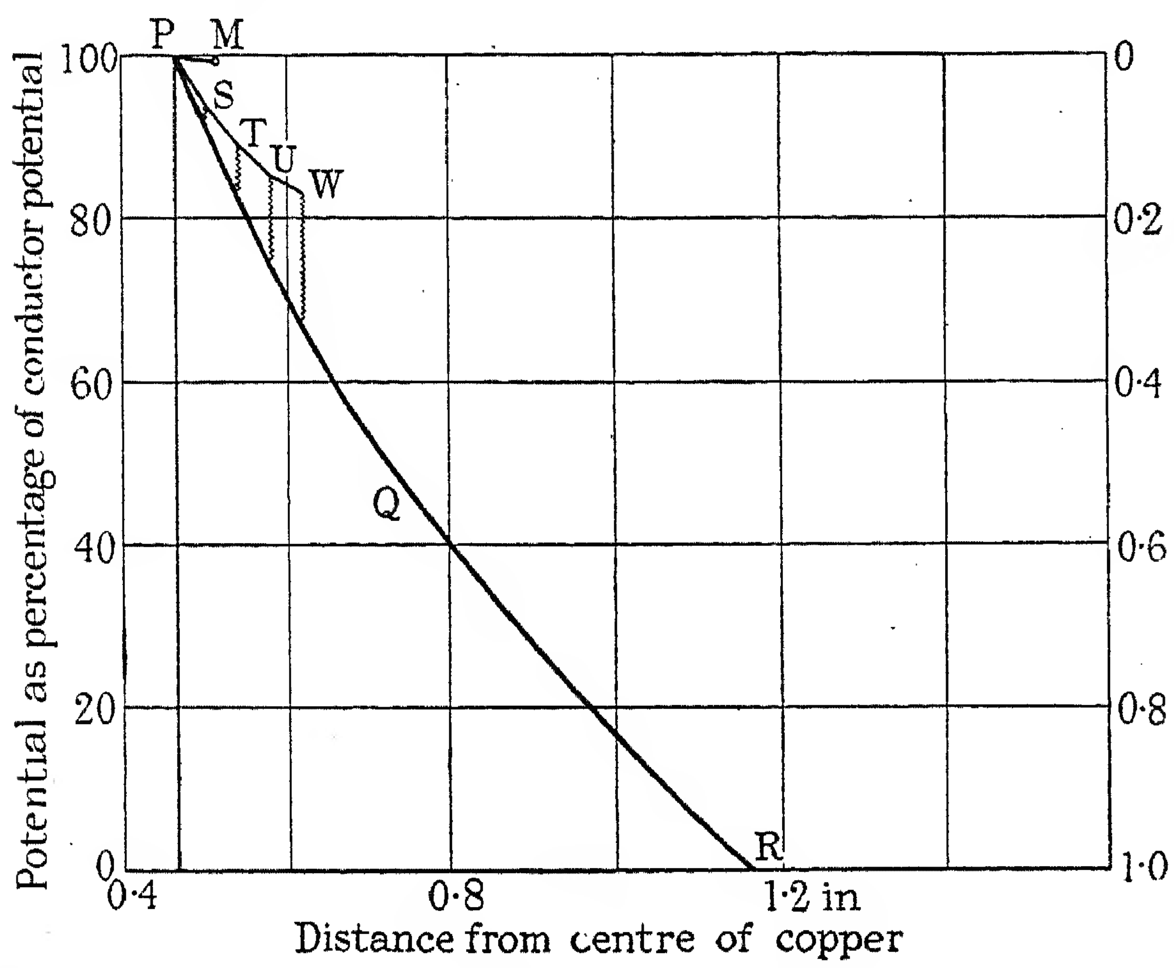


FIG. 3.—Mechanism of failure in voltage/time-to-breakdown tests, illustrating how tangential stress arises during breakdown.

PQR is the potential curve for a 0·5-sq. in. circular screened 66-kV cable, and is drawn to scale. To illustrate simply the production of tangential stress the dielectric is assumed to consist of 15 very thick papers. This does not affect the argument. The curve PSTUW is hypothetical.

beyond them, and that this drop is required for the ionizing-carbonizing mechanism occurring there.

In any case the slow carbonization mechanism clearly plays a large part in determining the shape of the time-to-breakdown curve. The individual papers are being worked well below the puncture or d.c. breakdown stress, and the only method by which failure can proceed is by carbonization of the compound radially and tangentially.

In practice two types of breakdown have been observed, commencing as described above and accompanied by extensive treeing but distinct in the later stages. One type is distinguished by a direct radial burn-out, while in the other the fault takes a long slanting path from the conductor to the sheath, following the treeing track as shown in Fig. 2. A. F. C. Adye has shown* that high-voltage, short-time tests on 66-kV cable give the radial type of breakdown, accompanied by severe local scorching of the paper, and the conclusion

* L. G. BRAZIER (see Bibliography, 22).

is that in such a test the final breakdown is due to thermal instability initiated by the intense liberation of energy at the centre of the deteriorating region.

The non-radial type of fault occurs at lower voltages where the heat evolution due to dielectric loss is much less and thermal instability does not arise, e.g. in service. In this case the tracking actually reaches the sheath, but owing to the high resistance of the former the current which flows through it is not necessarily sufficient to bring out the circuit breakers on a commercial feeder at once. In time, however, this track will be burnt down to a lower resistance and eventually a fault arc will pass, charring out a long slanting hole between copper and sheath.

The new technique of cable testing and cable dissection using the Schering bridge, sheath thermo-couples, and the dyed-paper test for wax, has so far enabled three distinct types of breakdown to be differentiated. Since deterioration arising from one cause may conceivably result in a failure of mixed type, as already explained above, it is safest to class the types according to their initial phenomena, as follows:—

(1) Tracking-type failure, with which this paper has exclusively dealt.
(2) Failure by thermal instability.*
(3) Disruptive failure.

The second is accompanied by scorching and is distinguished from the first by being free of waxing, treeing, and carbon cores, and in general by a cleaner type of fault. Further, the tracking-type failure starts, and progresses most rapidly, when the cable is off load (particularly when the load has just been removed), while the thermal type is started and normally completed at times of heavy load.

"Disruptive failure" is the name covering our ignorance of what takes place when a perfect cable is broken down by direct-current impulse voltage, or by a.c. stress sufficient to cause failure in a few seconds. The puncture is small, there is neither carbonization, waxing, nor scorching, no appreciable rise of temperature occurs, and with direct current there is no evidence of any time effect at room temperature, i.e. it appears that the cable will withstand indefinitely a voltage equal to 95 per cent of that which would break it down immediately. The stress required for this type of breakdown is of the order of six times the peak stress used for 100-hour a.c. breakdown.

(9) THE EFFECT OF DIRECT-CURRENT STRESS.

An understanding of the way in which the tracking mechanism causes failure in cables subjected to long-time a.c. stress enables us to realize why similar cable is able to withstand, for long times, the very high d.c. stresses mentioned above, and why no deterioration arises from such stressing.

It has already been mentioned (Section 3) that d.c. stressing of cables containing voids does not give rise to any waxing which can be detected by the very sensitive wax test. This leads one to ask whether ionization is absent, or whether it occurs but is insufficient to cause condensation of the oil.

* L. G. BRAZIER: *loc. cit.*

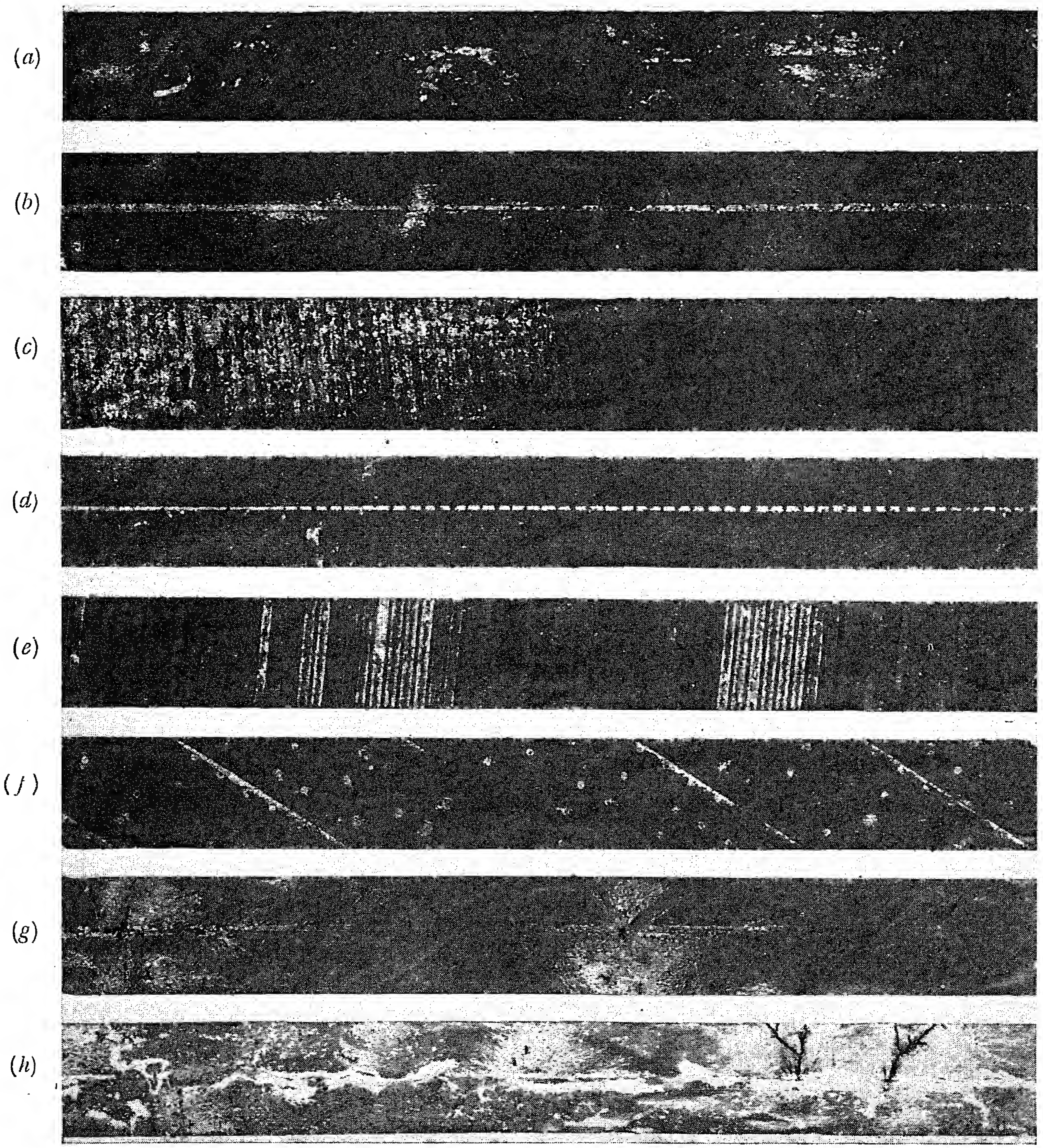


FIG. 4.—Individual papers from various cables, showing the types of waxing.

(a) Void waxing.
(b) Gap waxing.
(c) Strand waxing.
(d) Strand effect in gap.
(e) Strand-space waxing.
(f) Waxing at overlap and punch holes of conductor screening.
(g) Bush waxing.
(h) Severe void, gap, and bush waxing.

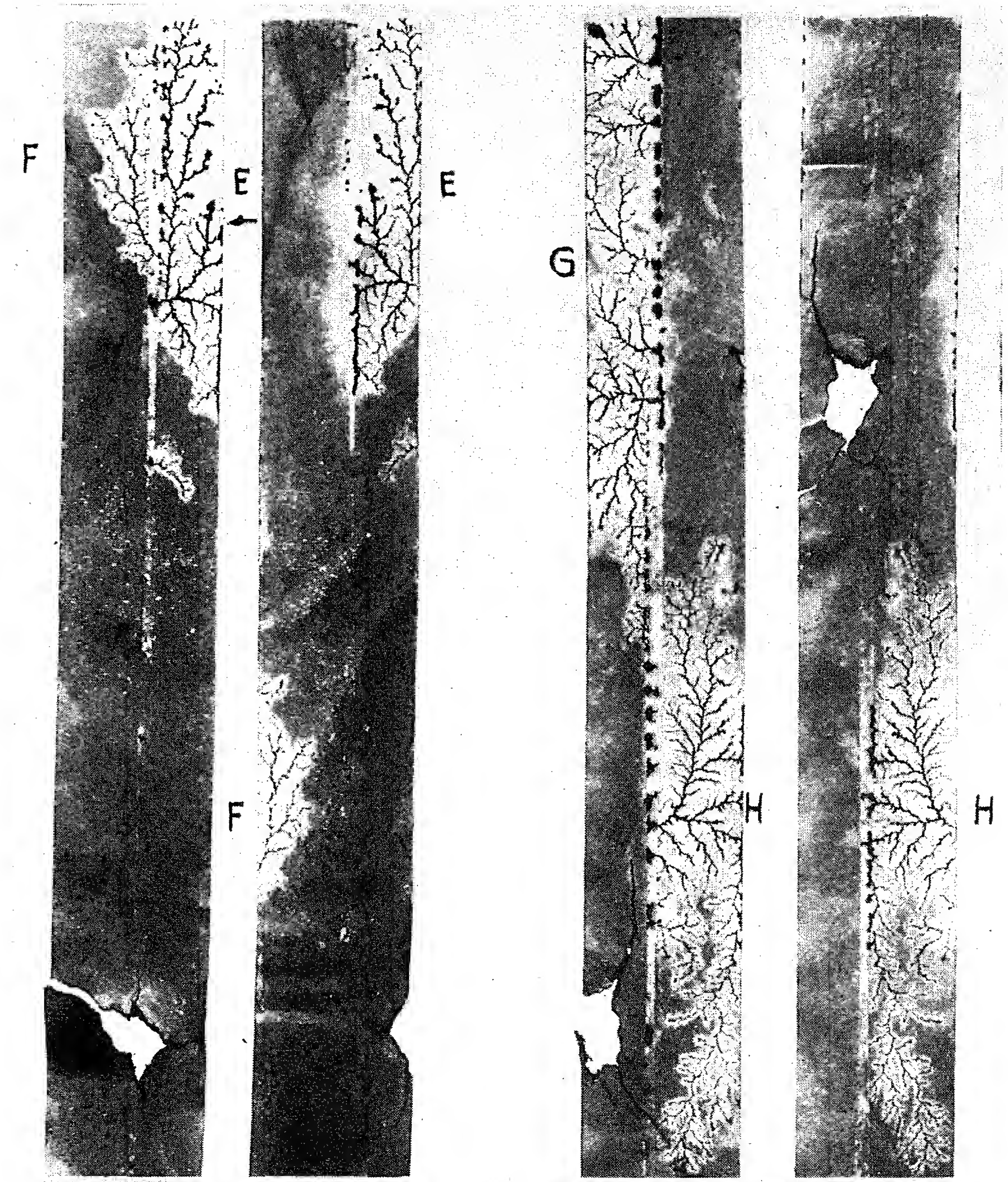


FIG. 5.—Individual papers showing treeing in impregnated cable under 200 lb. per sq. in. pressure.

Plate 2.

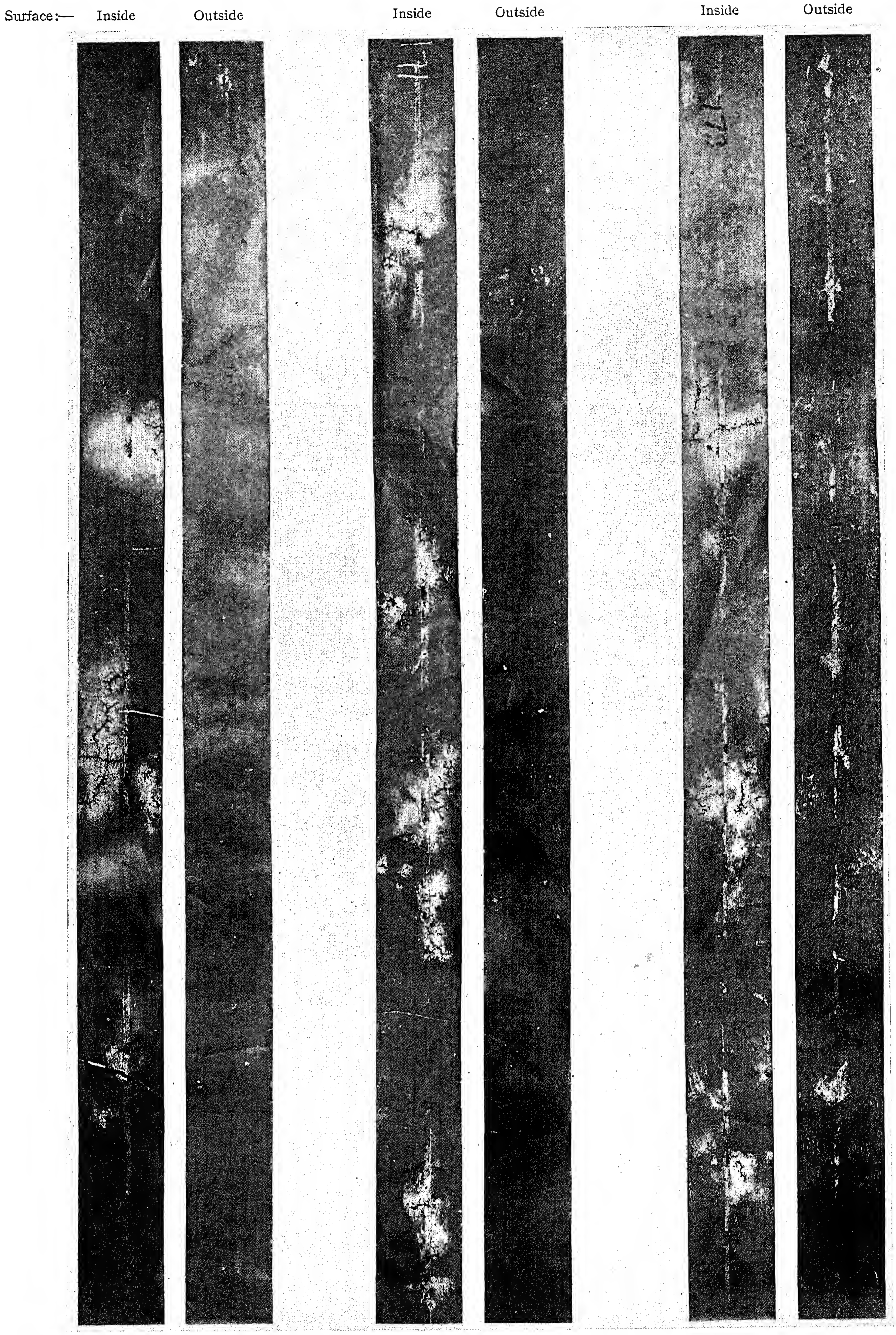


Fig. 6.—Individual papers showing treeing in impregnated cable at atmospheric pressure.

The following experiment, which has been repeated many times on different types of impregnated cable, gives an insight into the problem.

A drum length of cable was cut into 5-yard lengths and a number of the samples were tested on alternating current only, at suitable voltages so that a voltage/time-to-breakdown curve was established. The remaining samples were subjected to the same set of a.c. voltages but had in addition a d.c. voltage of the same value as the peak of the a.c. voltage superimposed upon them, the sign of the direct current being in some cases such that the resultant voltage between conductor and sheath varied from zero to a negative maximum of $-2\sqrt{(2)}V$, while for the others the limits were zero and $+2\sqrt{(2)}V$, i.e. in the first group the conductor never became positive and in the second group never negative. Fig. 7 shows graphically the resultant voltage applied to the cable in each case, and the method of obtaining this result. In Fig. 7 (*d*), B is a blocking condenser of large capacitance compared with the test cable, and serves to prevent the rectified current from passing through the transformer secondary while presenting a sufficiently low impedance to the a.c. charging current. Then, provided the leakages in the system are small, the superimposed d.c. voltage automatically reaches the peak value of the a.c. voltage applied to the test cable.

On comparing the performance of these three groups of cable it was found that the dielectric was completely indifferent to the presence of the d.c. stress, even though the value of the d.c. stress applied was more than five times the highest working stresses used in modern "solid" cable, i.e. the time to breakdown is determined only by the value of the a.c. voltage and is unaffected by the superimposition of a positive or negative d.c. stress.

The explanation of this at first rather surprising result is somewhat as follows.

The damage which the ions do to the paper-oil barrier depends on the speed with which they bombard it, the time, and probably also on the number of hits per unit area. The speed is a function of the stress in the void, but this stress is not simply the working stress of the cable at that point, since the stress is relieved or neutralized by the operation of the space charges.

In the case of d.c. stress alone applied to the cable the voids within it ionize when the stress across them reaches a sufficient value. The ionization continues until the space charges set up are of sufficient magnitude to reduce the stress below the ionizing value (Fig. 7*e*). A very small fraction of a second is sufficient for the completion of this process, so that the ionization under such conditions is merely a momentary flash sufficient to charge the opposite surfaces. The leaking-away of this space charge can be made up by leakage round the boundaries of the void. If the stress is slowly applied in the first instance the flash of ionization may never take place, the current required for the neutralizing charges having time to flow round the void.

On sudden removal of the d.c. stress the voids flash-ionize again in the reverse direction, as the space charges collapse together and neutralize one another. Thus a d.c. test lasting thousands of hours results at the most in a few flashes of ionization at switching.

Now when a.c. stress is applied to the cable the continual reversal of the polarity means a continual formation and collapse of space charge in every ionizing void space. This must be done 100 times per second when the frequency is 50 cycles per sec. In the short time of one half-cycle negligible charging can be accomplished

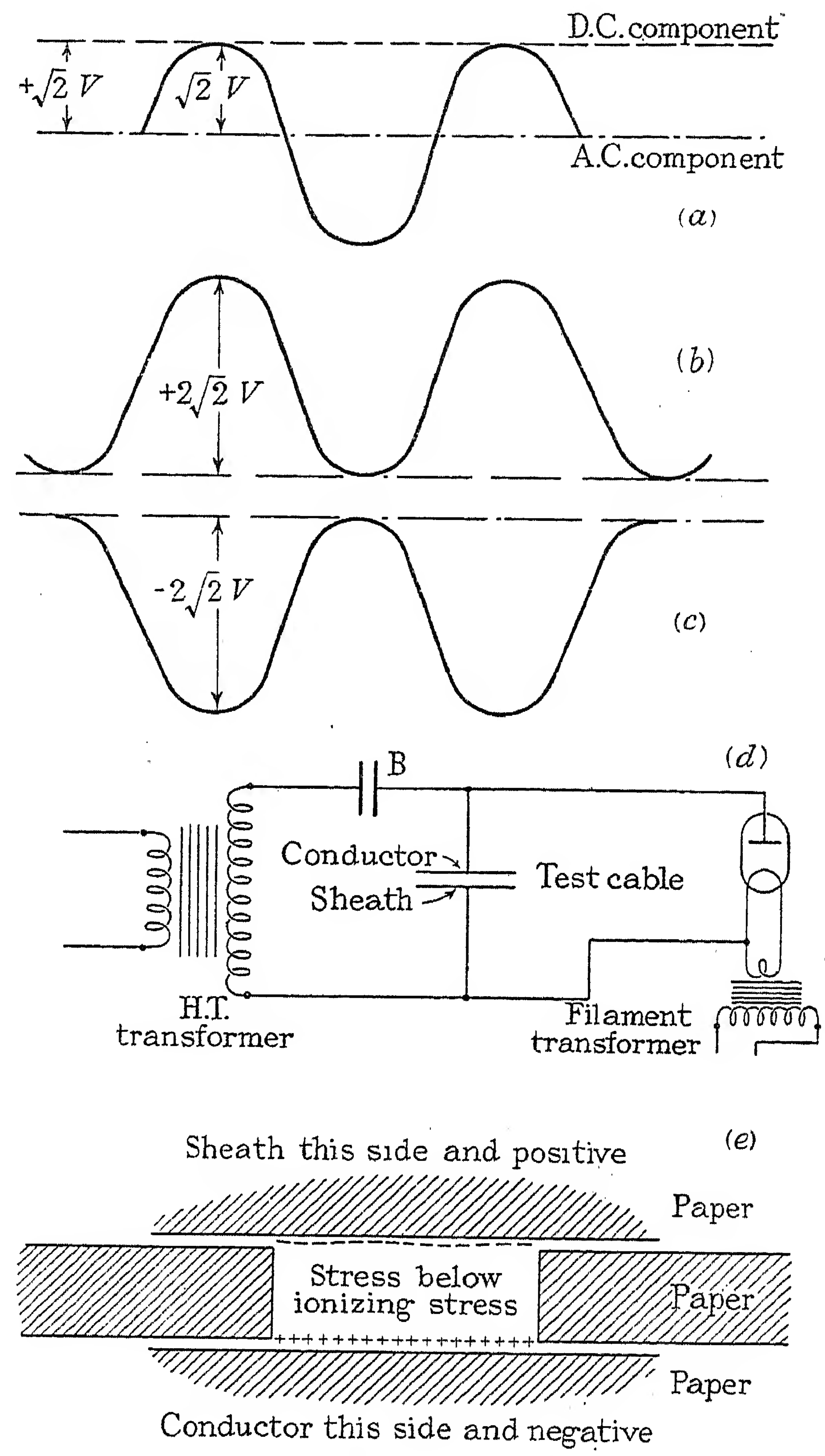


FIG. 7.—A.C. cable-testing with d.c. bias.

(*a*) The component voltages, when the position of the d.c. supply is connected to the conductor of the cable.
(*b*) The resultant voltage applied in the above case.
(*c*) The resultant when the negative of the d.c. supply is connected to the conductor of the cable.
(*d*) The circuit as connected to obtain (*c*).
(*e*) Steady-state condition in voids under d.c. stress; illustrating how space charge caused by ionization relieves the stress across a void. The ionization continues until the space charge is such that the resultant stress across the void is below the ionizing stress.

by leakage round the sides, and the whole current must be carried by ionization.

Thus while a d.c. test of 3 hours' duration results in at most two flashes of ionization (if the voltage is suddenly applied and removed) a 50-cycle test lasting the same time means more than a million volleys of ionization.

When the d.c. stress is superimposed on the alternating current as in the experiment described, the stress across

the voids is not doubled as might at first sight seem to be the case. The addition of the direct current merely means a piling-up of a permanent component of space charge in the void and not in an increase in the speed or number of the bombarding particles. It is for this reason that breakdown is a function of the a.c. stress and is not affected by the application of the direct current. This fact has for some years found very useful application in the routine d.c. testing of feeders at regular intervals.

It has been proved in use that by this means incipient faults, which would have caused interruptions to service if occurring later while the cable was in use, can be detected and removed with the minimum of trouble.

The maximum voltage recommended has been 5 times the r.m.s. working voltage. It is not surprising that the advisability of over-stressing cables to this extent should have been questioned. The practical answer is that the operation of the feeders after d.c. test has been freer of trouble than before such tests, while the laboratory results mentioned above certainly show that a d.c. stress of this magnitude does not shorten the life of the cable, even when applied for some hundreds of hours. Does a knowledge of the tracking mechanism help us to understand how the d.c. test succeeds in picking out incipient faults before they break down in service?

Consider the case of a track such as that depicted in Figs. 1 and 2, which has penetrated some way through the dielectric. In the case of a.c. stress it has been shown (Section 8) that the potential of the advancing head may be somewhat less than conductor potential because of the charging current carried by the track. When direct current is applied to the conductor the charging is rapidly completed and every part of the track is then at full conductor potential. Even at the highest d.c. stresses, however, no carbonization or extension of the treeing takes place before breakdown, because of the fleeting character of the ionization and the very small current densities involved.

Breakdown will take place between the outermost portion of the carbon track and the sheath when the applied voltage reaches the d.c. breakdown voltage for the particular thickness and quality of the dielectric concerned.

The d.c. "rupture voltage" of a given thickness of good-quality impregnated paper is fairly well known. It is thus possible in any given case to choose a d.c. test voltage which is sufficiently high to cause rupture where there has been a serious reduction of effective wall thickness, while being certain, on the other hand, that no rupture of good cable will take place.

(10) Application of the Theory.

It will now be profitable, in the light of the theory of deterioration evolved, to consider and interpret the experimental evidence already summarized, the results obtained by other investigators, and the changes in mechanism brought about by special conditions.

Smoothing the conductor causes an increase in the a.c. breakdown voltage because the severe local stresses at the conductor are thereby eliminated. Overlapping the papers near the conductor has a similar effect, as the large gap-voids are eliminated and a higher stress is required to cause equivalent damage. The elimination of the gaps also results in a slight change of the mechanism; ionization in a void between the first and second papers from the conductor causes an increased stress across the former, which results in fierce ionization of some small and possibly sub-microscopic gas bubble between the conductor paper and the crest of the strand. The ionized stream then develops as usual through the paper matrix.

Increase of the gas pressure in the voids decreases the severity of the ionization by reducing the mean free path of the electron. Conversely, decrease of the pressure increases the mean free path and leads to a lower a.c. breakdown voltage. In practice such a decrease of pressure takes place when the cable is cooling; hence the tendency for tracking failure to occur on cooling as mentioned above. Both waxing and the measurable high-frequency discharges are particularly severe when the compound column "breaks" at any point due to the compound contraction,* and if such a "break" occurs in the dielectric near the conductor, while the cable is under high electric stress, coring will invariably be found there.

Since coring is believed to be due to penetration by the ionic stream followed by carbonization of the compound in the inter-fibre spaces, the fibres themselves being unaffected, it is to be expected that the resistance of papers to this type of breakdown will be greater the closer the fibre structure becomes, i.e. the lower the porosity. This can be shown to be the case both for impregnated cable and for impregnated test condensers.

Fig. 8 shows the relation between the porosity† of the manila papers composing a test condenser and the breakdown voltage (short-time value).

Experimental cables were also made with these papers, and the curve obtained by plotting time to breakdown at a given voltage against porosity (Fig. 9) shows quite definitely the advantage to be obtained by a decrease in the porosity of the paper.‡

Evidence of the same nature is given by Emanueli.§ Comparative condensers were made up with low-porosity papers sandwiched between high-porosity (filter) papers, and vice versa, the number of sheets of each sort of paper being the same for the two cases. On voltage/time-to-breakdown tests the condensers with the filter paper adjacent to the electrodes gave an "asymptotic value"‖ of 260 kV/cm, while the corresponding value for the low-porosity papers was 300 kV/cm.

The normal condensers tested by Emanueli were impregnated under vacuum in thin oil. In order to observe the effect of including air, thick oil was used and air deliberately let in. The "asymptotic" breakdown value was reduced thereby from 320 kV/cm to 150 kV/cm, showing very clearly the effect of gas inclusions.

The fact that even in the breakdown of impregnated condensers it is the quality of the papers near the electrodes which exerts the major influence makes it very probable that the failure in such condensers also originates by coring from the electrodes. Arrested breakdown cannot be obtained in these cases because

* See Section (11).
† Absolute porosity, as defined by Emanueli in his book "High Voltage Cables" (Chapman and Hall, 1929).
‡ See Bibliography, (11).
§ *Ibid.*, (16).
‖ Asymptotic value. The limiting stress value to which the curve tends at long times (100–300 hours).

the stress must be very high to start the process and then failure follows very quickly. If the surface charging current is greatly increased by testing at a high frequency, however, the beginning of the process can be detected and arrested breakdowns may be obtained. In such cases a small tree is formed on the paper surface opposing the progress of the track, exactly as in cables.

The possible origins of a gas-filled or void space in the dielectric are:—*

(*a*) Manufacture.

(*b*) Severe mechanical treatment.

(*c*) Evolution of dissolved gas due to change of temperature or pressure.

(*d*) Drainage.

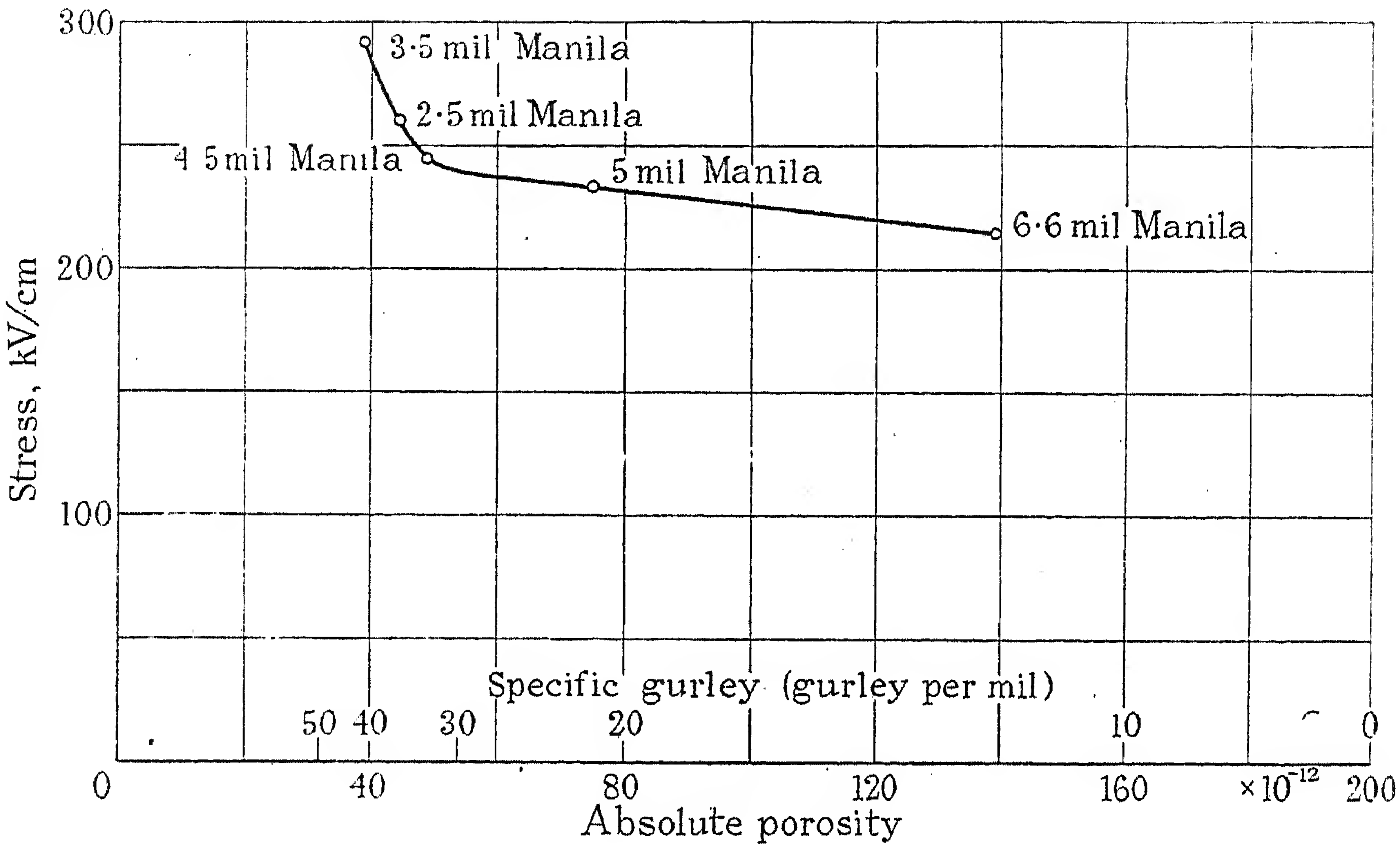


FIG. 8.—Relation between short-time a.c. breakdown stress of impregnated test condensers and porosity of paper of which condensers are made.

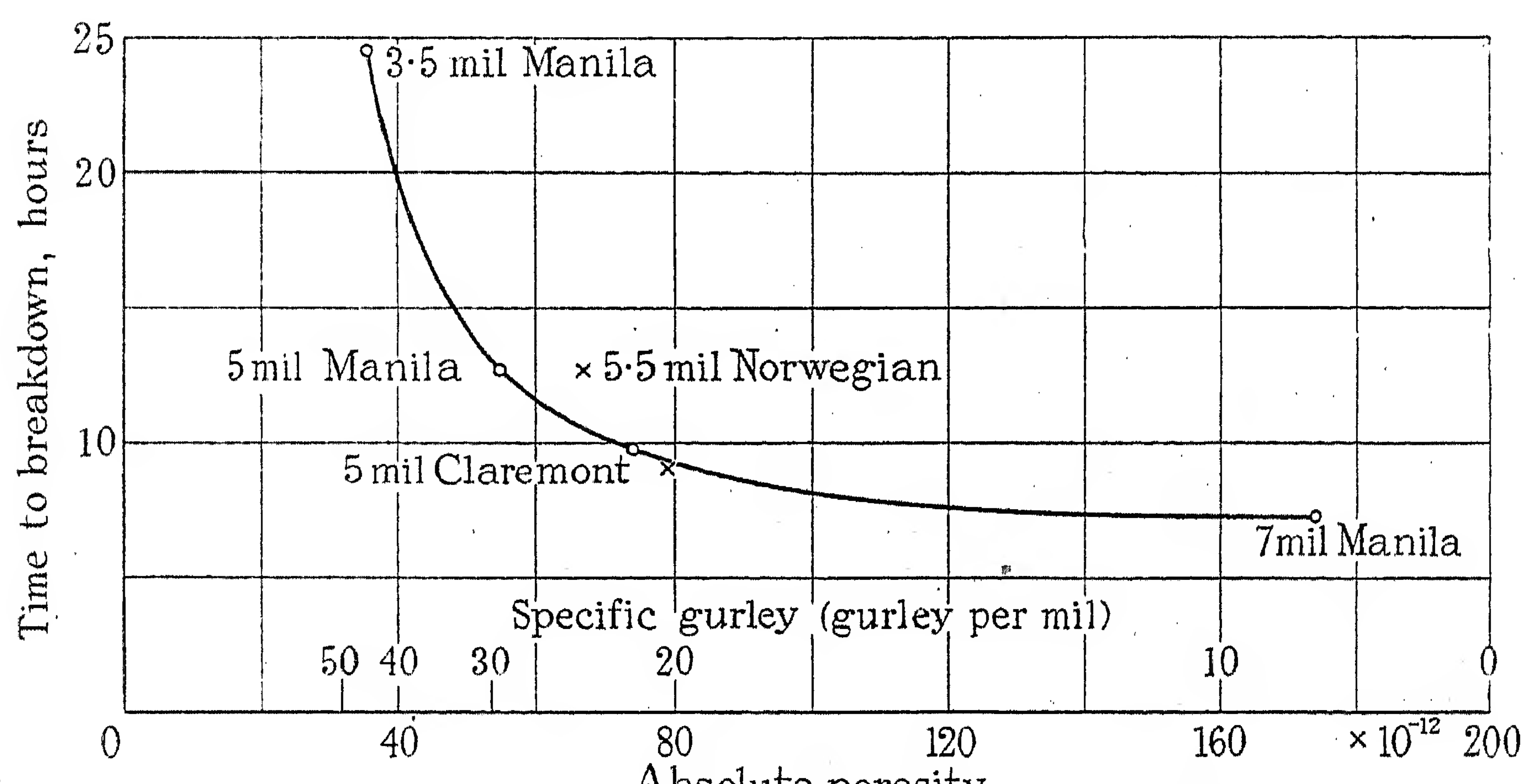


FIG. 9.—Effect of porosity of the paper on the time to breakdown of impregnated-paper cable. 0·25-sq. in. stranded cable; 0·33-in. wall. Time to breakdown at 99 kV (max. stress 171 kV/cm). All cables made with 40 : 60 overlay.

(11) VOIDS, THEIR FORMATION AND INFLUENCE.

The fact that tracking in all the cases examined commenced either at the conductor or at the sheath does not, of itself, exclude the possibility of breakdown by a linking-up of the voids within the dielectric, and it is therefore desirable to discuss here the occurrence and effect of gaseous spaces within the cable in the light of the very definite evidence provided by the magenta wax test.

(*e*) "Cavitation" on cooling.

(*f*) Gas produced in the condensation process due to void ionization nearby.

(*g*) Gas produced by treeing from the conductor or sheath.

The term "drainage" is to be understood as covering any case where voids are formed due to the flow of compound by gravity. The normal cases are:—

* See Bibliography, (21).

(i) Flow within the cable while standing on the drum.
(ii) Bleeding when opened or cut for jointing, etc.
(iii) Flow on gradients and vertical rises.

Obviously, (i) may be severe if the cable stands in the sun, or is shipped near boilers, etc., and (iii) becomes increasingly important as the operating temperature rises.

The wax test indicates that the sheath and strand spaces drain first, and that these are followed by the helical gaps in the body of the dielectric.

In all these cases air replaces the compound in the drained spaces, this air either having been present originally or creeping in under atmospheric pressure.

In well-manufactured and carefully-handled cable, (*a*), (*b*), and (*c*), are absent, and if a sample is V.T.B.* tested in such a way as to prevent drainage, no ionization or waxing will take place until the " tracking breakdown " commences from the conductor, i.e. until the maximum stress exceeds about 150 kV/cm.

If, however, the same sample is subjected to load cycles " cavitation " will invariably occur on cooling, and if the voltage is applied during this period ionization and waxing will take place. By " cavitation " is meant a " break " of the compound analogous to that which occurs in a water or oil pipe when the pressure is too low.† Possibly in cable this " break " actually results in the evolution of gas or vapour from the paper or compound, and from this point of view (*c*) and (*e*) are similar; (*c*) being meant to cover the results of poor degasification, etc., while " cavitation " must occur, however perfect the cable, e.g. the Toricellian vacuum in a barometer. Clearly for cables in a vertical position drainage and " cavitation " will combine in determining the void formation.

It is not known whether further gas is produced in mid-dielectric voids in conjunction with the waxing, or to what extent the gases, if produced, are able to spread in the longitudinal or radial directions and thus cause further void spaces and additional waxing. The well-defined character of void and gap waxing in many long-time tests suggests that such travel is either limited or does not occur at all. No case has been observed, even at the highest stresses, of the ionized films linking up electrically from layer to layer across the surfaces and through the gaps in the way that has been suggested by many cable engineers. The reason for this has become apparent from the visual studies of ionization now being made. Inter-layer ionization causes only a very slight distortion of the electric field, and the stress component tangential to the paper surface is not of sufficient magnitude or extent to give rise to the tangential ionization which would provide the " linking " mentioned above.

On the other hand, the tree advancing from the conductor produces very severe and extensive stress distortion, and the resultant tangential ionization leads to inter-layer linkage, as already described in Sections (5) and (8).

The tree discharge not only advances from gap to gap and paper to paper as described, but it produces a considerable amount of gas by condensation of compound into wax, and we have reasonably good evidence that this gas (*a*) " prepares the way " for the further progression of the discharge, and (*b*) spreads to a limited extent along the helical gaps in directions other than that taken by the discharge itself.

The action (*b*) is purely mechanical, as shown by the way it follows the path of least resistance, and does not creep between the paper surfaces. It is due to the pressure of gas produced forcing the compound away.

The action (*a*) is mainly the result of the ionic bombardment acting on the oil film which it meets. This bombardment has the same effect as a gas pressure, but acts only in the direction of the field, which in the case discussed is tangential to the paper surface. Hence the gas in this case progresses not helically but longitudinally, parallel to the conductor, the " pressure " being sufficient to drive out the oil between adjacent paper layers.

(12) Conclusions.

(1) Breakdown of impregnated cables normally takes place as a result of the slow carbonization familiar to the cable engineer as " treeing." In single-core cable the carbon track can always be traced back either to the conductor or to the sheath, almost always the former. The carbon is formed from the compound, not from the paper.

(2) There is as yet no evidence that waxing, which can occur isolated in any part of the dielectric, affects or accelerates this type of breakdown in any way. On the other hand, treeing is always accompanied by waxing in its immediate vicinity.

(3) It is believed that moderate void ionization does not produce gas cumulatively, and, further, that it does not link up electrically from one gap to the next above, thus reducing the dielectric wall.

(4) The vigorous conductor discharge which leads to treeing produces a quantity of gas which (*a*) spreads longitudinally by electrical bombardment, thus linking one gap to the next above, and (*b*) spreads helically by expansion under its own gas pressure.

(5) For the carbon tracking to continue its progress through a paper or over a surface a certain " current density " must be exceeded, and it appears that for modern single-core cable, even at stresses many times greater than the present working values, discharges of the requisite density commence only at the conductor or sheath, and never in voids within the dielectric.

(6) Other things being equal, the " current density " is large for high frequencies, and very small in the case of d.c. stress; hence breakdown by slow carbonization along a track is not possible with direct current, and for this reason the d.c. breakdown voltage does not depend to an appreciable extent on the duration of application.

(7) The carbonization mechanism is a major factor in the well-known voltage/time-to-breakdown curve for alternating current, a high voltage resulting in quicker development of the cores and trees. The voltage to which this curve becomes asymptotic is the voltage below which no coring of the papers next to the conductor takes place.

* V.T.B. test = Voltage/time-to-breakdown test, i.e. an excess-voltage test without application of loading current.

† The same term is used by marine engineers in propeller design. In this case the " break " is caused by local low pressure due to the propeller speed.

(8) Breakdowns in service, under stability test and on short-time test (10–200 hours), all appear to originate in the same manner; but, with the highly-stressed test samples, thermal instability induced by the heat of deterioration causes direct breakdown when the deterioration has penetrated through about one-sixth to one-quarter of the total dielectric, whereas when the stress is lower, as in service, the tracking extends much farther, sometimes even to the sheath. The resistance of such a carbonized track is initially very high, and it is probably "burnt down" until the current is sufficient to bring out the circuit breakers.

(9) The initiation of the process of carbonization through the papers near the conductor is delayed or prevented by

(*a*) Decreasing the maximum stress;
(*b*) Avoiding gaps or voids in this region; and
(*c*) Decreasing the porosity of the paper.

(10) The great discrepancy between the a.c. breakdown strength of small laboratory samples of impregnated paper and that of cables is due to the fact that the latter always contain voids near the conductor comparable in size with the helical gaps, while voids in the former if present are very much smaller, and may even be sub-microscopic.

ACKNOWLEDGMENTS.

The author wishes to express his gratitude to Mr. J. Urmston and to Dr. L. G. Brazier for suggestions and much helpful criticism during the progress of the work.

Thanks are due to Callender's Cable and Construction Co., Ltd., in whose research laboratories the work was carried out, for permission to publish this material. The author is indebted to his colleagues for co-operation in many respects, and to Mr. G. King for untiring assistance in the laboratory.

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Cable wax is neither fusible nor soluble in any solvent available.

(2) FARMER, F. M.: "The Wax Test," *ibid.*, 1926, vol. 45, p. 553.

Electrical Testing Laboratories Report No. 66173. A test designed to show the susceptibility of various oils and compounds to waxing. May be criticized in view of Hirshfield's result that the state of degasification is a controlling factor.

(3) HIRSHFIELD, C. F., MEYER, A. A., and CONNELL, L. H.: "Mechanism of Cable Failure." (Printed but not published Detroit, 1927, by the Association of Edison Illuminating Cos.) See also *Electrical World*, 1927, vol. 90, p. 987.

Cable oils under bombardment give "wax" and hydrogen. Wax is a good dielectric, its presence does indicate deterioration, but wax is not the cause of failure. Life is not dependent on the flatness of the power-factor/temperature* curve. Gaseous ions can penetrate through dry paper because of its open structure. The location and amount of wax is suggested as a criterion for the presence of the silent electric discharge. Solvents may be used to extract the oil, thus rendering the wax more easily visible. The greatest quantity of wax occurs in the gaps. The use of thinner and butting papers is suggested to reduce the size of the gaps. Tests on vaseline stressed between glass walls. When the vaseline was degasified before pouring in, no waxing took place. Waxing was accelerated by sodium tungstate. (Alkaline earths give off electrons freely.) A rectifying action due to ionization was found, and the authors suggest that this may lead to a.c. plus d.c. stress and accelerate breakdown. (Our tests have shown that d.c. stress up to values in excess of the a.c. stress have no appreciable influence on breakdown.)

(4) SHANKLIN, G. B., and MACKAY, G. M. J.: *Transactions of the American I.E.E.*, 1929, vol. 48, p. 338.

Wax is not formed by stress alone. Capacitors have operated for years at 160 kV/cm without formation of wax.

(5) WYATT, K. S., SPRING, E. W., and FELLOWS, C. H.: *ibid.*, 1933, vol. 52, p. 1035.

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(6) CLARK, G. L., and MRGUDICH, J. N.: *Electrical World*, 1934, vol. 103, p. 284.

X-rays reveal successive steps in cable-oil deterioration.

(B) **Mechanism of Breakdown in Impregnated Paper Cables.**

(7) DEL MAR, W. A., and HANSON, C. F., *Transactions of the American I.E.E.*, 1924, vol. 43, p. 947.

The control of breakdown strength by control of paper porosity is mentioned. Describes treeing found in single-conductor cable and puncture through the papers lying between this and the conductor. "Other hot spots of a similar character were found, which, however, did not extend to the conductor but were confined to the intermediate layers of tape." (Clearly the coring connecting this treeing to the conductor was so small as to be missed without microscopic examination.)

(8) DUNSHEATH, P.: *Journal I.E.E.*, 1926, vol. 64, p. 97.

The time-to-breakdown curve is related to the formation of the treeing, and a theory is evolved to explain how the tangential stress arises. [See comments on (7) and (20).]

(9) EMANUELI, L.: *Electrical Review*, 1926, vol. 99, p. 1050, also *Electrical World*, 1927, vol. 90, p. 601.

The penetration of gas through the papers under the action of the ionization is clearly described.

(10) CARR, J. L.: *Journal I.E.E.*, 1926, vol. 64, p. 144 (in discussion).

Cable breakdown is due to breakdown of the compound starting from the point of maximum stress. Use of the microscope mentioned. This suggestion was

* See Bibliography (22).

quashed and it was maintained that treeing affects the fibres, as can be seen by extracting the oil, when the tree remains. (As shown in the present paper, the tree remains because it is integral with the waxed deposit.)

(11) DAVIS, E. W., and EDDY, W. N.: *Transactions of the American I.E.E.*, 1929, vol. 48, p. 373.

Includes experimental work on the effect of paper porosity on electric strength.

(12) EMANUELI, L.: "High Voltage Cables" (London, Chapman and Hall, 1929).

(13) RILEY, T. N., and SCOTT, T. R.: *Journal I.E.E.*, 1929, vol. 67, p. 946.

"One point of view . . . is that compound is added to prevent breakdown of the air spaces in the paper, which is the main dielectric."

Higher electric strength is obtained by close packing of fibres than if the same porosity is attained by hydration of the pulp.

(14) BROWN, S. G., and SPORING, P. A.: *ibid.*, 1929, vol. 67, p. 968.

D.C. stress causes no energy loss in voids. The damage caused on alternating current will increase with frequency.

(15) HAWKINS, H.: *ibid.*, 1929, vol. 67, p. 985 (discussion).

". . . The effect of surges or transients on healthy cables is negligible."

(16) EMANUELI, L.: Congrès International d'Électricité, Paris, 1932, Paper 9.

(17) WHITEHEAD, J. B.: "The Life of Impregnated Paper," *Transactions of the American I.E.E.*, 1933, vol. 52, p. 1004.

Concludes that life is independent of dielectric power factor (small samples) but depends on impregnation and on the penetration power of the oil. Breakdown values are much higher than those obtained in practice. (In the light of present knowledge it is probable that the penetrative power is important in Whitehead's case because the penetrating oil is enabled to get into very small interstices in the paper, e.g. into capillaries. In solid-type cables, where sooner or later there will be gap voids, penetration is of less importance and the necessity of "clogging" the larger interstices and of preventing drainage is of greater importance than capillary impregnation.

Whitehead suggested that he was obtaining some sort of thermal failure, because of the time taken and the rise of temperature and power factor just before failure. From his description there is no doubt that the failures were initially of the ionization type.)

(18) TYKOCINER, J. T., BROWN, H. A., and PAINE, E. B.: University of Illinois, Bulletins Nos. 49 and 50, August 1933.

Investigation of cable ionization characteristic with discharge detection bridge.

(19) SCOTT, J. A.: "The Effect of High Oil Pressure on Cable Insulation," *Transactions of the American I.E.E.*, 1933, vol. 52, p. 1013.

Oil pressure greatly improves the long-time a.c. breakdown strength but does not affect the impulse breakdown. (Since the impulse breakdown is presumably not of the ionization type this is to be expected.)

(20) DEL MAR, W.: *ibid.*, 1933, vol. 52, p. 1015 (in discussion).

Treeing normally occurs about one-third of the dielectric wall from the conductor. The reasons suggested have been:

(a) An energy/distance effect such as occurs for corona round a wire.

(b) Impregnation takes place from conductor and sheath, leaving a "dead end" of entrapped air in this region. The hydrophil test [see Bibliography (5)] does not support this.

(c) That the region concerned is at the greatest thermal distance from the combined thermal sink given by the sheath and the conductor.

(The necessity of finding a reason of this sort is removed by the present paper. The breakdown takes place from the electrode, and increasing tangential stress is the reason for the "maximum deterioration" one-third of the way through. The induced thermal breakdown prevents it travelling more than this distance in most cases.)

(21) SAY, M. G.: *World Power*, 1933, vol. 19, p. 79.

Discusses the possible origins of void spaces in impregnated cable.

(22) BRAZIER, L. G.: "The Breakdown of Cables by Thermal Instability," *Journal I.E.E.*, 1935, vol. 77, p. 104.

APPENDIX.

TECHNIQUE OF EXAMINATION OF ARRESTED FAILURE.

The papers are removed from the faulty section of cable until the deterioration shows up through the papers. The dielectric is then cut circumferentially at two points, so as to include, if possible, the whole of the region deteriorated between these two cuts.

The papers in the section so cut are then removed, and each paper is marked on the inside at the end adjoining the nearest sealing end, with the cable sample number and paper number (counting from the sheath). At the change of lay, special care is required. The last paper of the lay is doubled back on itself about 1 in. at the tapered end, and a mark made on the top paper of the next lay at the corresponding point, so that the two can subsequently be located. The mutual positions of the papers in any group of six are given by the diagonal cuts at the ends, together with the gap waxing marks. The punching of two small holes through the dielectric, $\frac{1}{4}$ in. to $\frac{3}{4}$ in. apart, before removal of the samples, greatly assists in location should the gap waxing be too faint.

It is advisable to remove the papers on the adjacent sections of cable, paper for paper, with those of the test section between cuts, and to take further samples if the deterioration extends beyond the section originally cut. The additional samples are numbered as the others, with the addition of some distinguishing mark or letter.

The samples should be rubbed as little as possible, as in the advanced stage the whole of the waxing and treeing is liable to flake off, especially after extraction.

The samples having been extracted and dyed, detailed examination may now proceed at the office desk. While it is possible to examine the path of deterioration by

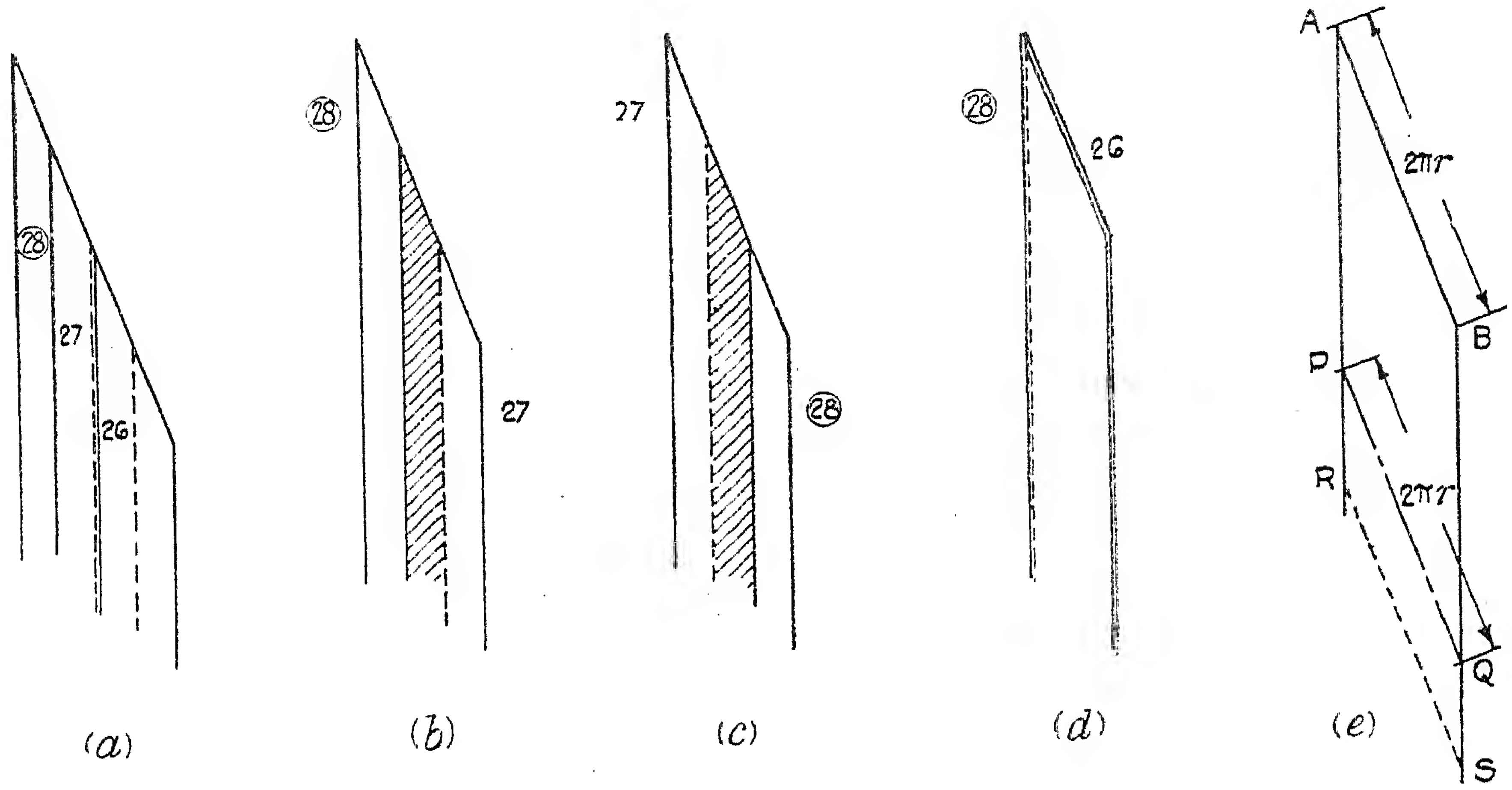


FIG. 10.—Re-location of cable papers.

winding the papers back on to a mandrel of the appropriate diameter, it will be found much quicker to locate them mutually on a flat surface, following rules which may best be explained by means of an example.

Consider the three papers 26 to 28 (Fig. 10), with 50 : 50 overlay. When unrolled as a group on to a plane surface, the appearance of the ends will be as in (*a*). Drawing papers 27 and 28 alone it is clear that the common area is that shown shaded in (*b*). But these two papers are also in contact over the areas unshaded in (*b*). This contact, and the necessary positions of the ends, are shown in (*c*). For any overlay other than 50 : 50, the position must be modified accordingly.

In addition to the direct contact between these paper surfaces, there is

(i) The possible path from 28 to 26 through the gap of 27.

(ii) The possible path from edge to edge of any paper across the gap between its edges.

In the example given (i) is obtained by direct superposition of 28 on 26 as in Fig. 10(*d*). This again must be modified for overlays other than 50 : 50, but the gap waxing, or failing that the holes punched as recommended above, greatly assist in this location, once the general rules are appreciated.

To examine the possibility (ii) it is only necessary to realize that the contiguous points when the paper is on the cable are one circumference separated from each other measured diagonally across the paper at the same angle as the diagonal end-cut, which is itself one circumference long, e.g. in Fig. 10(*e*), P and Q are contiguous points because they are the extremities of a line parallel to the cut edge AB, likewise RS.

At the change of lay, gap-waxing frequently shows exactly the position of the cross-overs, but in order to examine, say, a core at X, care must be taken that the papers are located as shown by Fig. 11; the triangular cuts A and B must be in the same straight line and not merely parallel to each other. These rules are readily appreciated by actually unwinding a few papers with mutual location in mind.

Examination should be started with the papers near the conductor. The third or fourth paper out from the

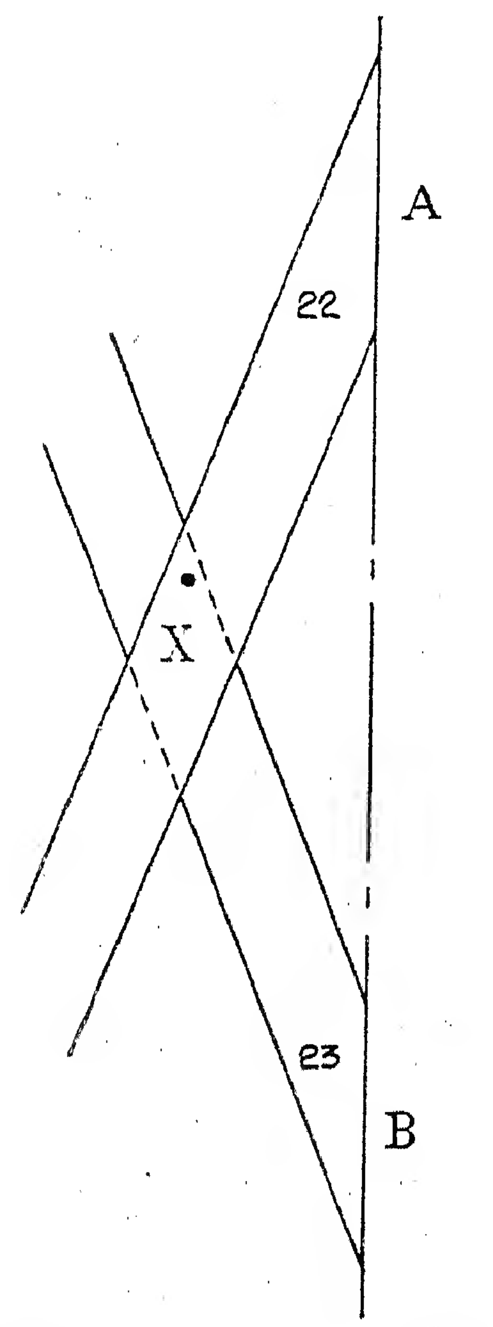


FIG. 11.—Re-location of cable papers at the change of lay.

copper will generally show some small pock-marks, and these assist in finding the still smaller marks or punctures in the second paper out. In this way, by tracing back, it is possible to find from which point or points the main deterioration started.

[The discussion on this paper will be found on page 116.]

THE BREAKDOWN OF CABLES BY THERMAL INSTABILITY.

By L. G. BRAZIER, Ph.D., B.Sc., Associate Member.

(*Paper first received* 21*st November*, 1934, *and in final form* 22*nd February*, 1935; *read before the* TRANSMISSION SECTION 20*th February*, 1935.)

SUMMARY.

An approximate method is described by which the problem of thermal stability of the cylindrical dielectric of a cable can be investigated. This involves the problem of deducing the dielectric loss angle* against electric stress characteristic, for the given dielectric, from measurements of dielectric loss angle against voltage made upon a cable; and methods are described for carrying out this conversion. Predictions made by these methods are supported by experimental results. The post-mortem characteristics of thermal-instability failures are described, so that these can be diagnosed and distinguished from failures of the tracking and other types. An account is given of the cable failures met with in excess voltage testing in the laboratory, in which there is a transition from breakdown of the tracking type to a final breakdown by thermal instability.

In studying the breakdown of cables, two main classes of breakdown mechanism have been delineated, apart from the case of instantaneous dielectric rupture which only occurs with excessively high voltage. One class, which has been termed "tracking breakdown," has been fully described by Robinson.† The second main class is breakdown by thermal instability, and the purpose of the present paper is to describe methods of determining the incidence and general characteristics of failures of this type. These two classes overlap in some respects. As described later in the paper, breakdown purely by the tracking mechanism is rarely completed, but at a certain stage the extra heat generated by the tracking mechanism results in the dielectric being thrown into thermal instability. A study of the transition point in different classes of cable and under different test conditions has proved to be of great interest.

The breakdown of dielectrics by thermal instability has been discussed for a long time, and a voluminous literature exists, of which a valuable account has been given by Whitehead.‡ Very little attention, however, appears to have been paid to the question of thermal instability in cables. This is probably due to the difficulty of any rigid mathematical treatment of the case. Occasionally, where the matter has been mentioned, an inadequate method of treatment has led to the erroneous view that there is only a remote likelihood of thermal instability arising in cables under ordinary conditions of usage.

The present investigation was started as a matter of laboratory interest in order to get a thorough understanding of some cable failures that had occurred under severe testing conditions. As the problem became clearly analysed, however, it was realized that the results were of immediate importance not only to the regular working of a cable research laboratory, but also to the case of cables of the higher voltages under normal service conditions.

The work of a cable research laboratory must, at the present time, be directed along two main channels:—

(*a*) The resistance of the dielectric to breakdown by the tracking mechanism must be improved by studying the conditions controlling the formation of the first microscopic core of the Robinson mechanism.

(*b*) For the higher-voltage cables the thermal stability of the dielectric must be improved by obtaining dielectrics in which the dielectric loss angle* does not show a steep rise with temperature.

These two lines of development interact closely. As resistance to the tracking breakdown mechanism is improved, higher test-voltages become necessary, but it is essential that the test conditions be controlled so that thermal instability is avoided if the tests are not to fail entirely in their purpose. It is, in fact, nearly true to say that, even if a considerable improvement in resistance to the initiation of tracking breakdown were to become available at the present moment, it would still not be possible to operate cables of the normal solid type at the highest voltages, without first obtaining an improvement in the D.L.A./temperature characteristic.

It is also found that the thermal stability of the dielectric is of importance in the case of 66-kV cables if any increase in the temperature rating of the cables is contemplated, and it may be said to be of controlling importance in the case of 132-kV cable.

The main features of thermal instability have been frequently presented. A dielectric situated in an electric field (and particularly in an alternating-current field) becomes the source of a continuous generation of heat. This heat has to be dissipated into the surrounding thermal sink, via the thermal resistance of the dielectric itself and of any other material that may be interposed. In any particular case, equilibrium can only be reached when the heat generated under the particular thermal and electric conditions equals the heat that can be dissipated under the same conditions. The point of equilibrium can be determined by drawing two curves, one of heat generated and the other of heat dissipated, as a function of temperature, and observing their intersection.

As an example, in Fig. 1 the curved line may be supposed to be a curve of heat generated in the dielectric.

* See footnote in col. 2.

† D. M. ROBINSON: "The Breakdown Mechanism of Impregnated Paper Cables," *Journal I.E.E.*, 1935, vol. 77, p. 90.

‡ S. WHITEHEAD: "Dielectric Phenomena," III, pp. 226–259.

* A universally accepted nomenclature for dielectric loss has, unfortunately, not yet been set up. The term "power factor" is confusing on account of the electrical engineer's use of the term in relation to the angle ϕ between an admittance vector and the vector corresponding to a pure resistance. In dielectrics, however, the angle which is of interest is the angle between the admittance vector and a vector 90° from a pure resistance. In this paper, this angle is denoted by the term "dielectric loss angle," δ, and the contraction "D.L.A." is used.

Many dielectrics exhibit a characteristic of this general type, in which the heat-generated line curves upwards with increase of temperature. This is a necessary result of the familiar upward curvature of the D.L.A./temperature curve of most cable dielectrics.

The full straight line is a curve of thermal dissipation, and the intersection L shows the conditions at which equilibrium will be reached. If, however, additional thermal resistance is interposed the slope of the dissipation line is reduced. The equilibrium point L moves to the right until a critical case occurs at M, when the line is tangential to the curve. Alternatively, the thermal resistance may be left unchanged, but the ambient temperature θ_a, i.e. the temperature of the infinite sink, may be increased. In this case, the dissipation line moves to the right, remaining parallel to its first position.

Again, a critical case occurs at N, when the line is tangential to the curve. At both these points M and N, it is clear that any slight disturbance of the temperature upwards will result in the generation of an amount of additional heat greater than can be dissipated. From this point, therefore, the temperature will progressively rise until burning, breakdown, or some other phenomenon, intervenes.

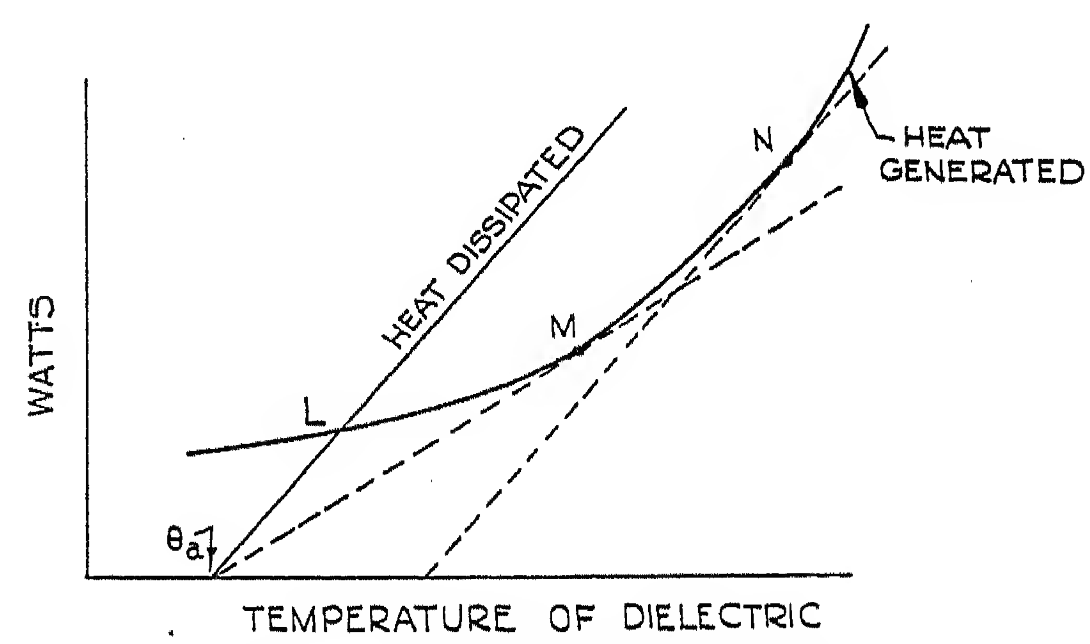


FIG. 1.—Thermal-stability diagram.

The mathematical treatment of this problem rapidly becomes complicated. The general equation can be written down, and Whitehead's* account shows that a number of special solutions have been obtained. In all cases, however, the conditions have been specially simplified with a view to obtaining alignment between theoretical and experimental results. In particular, the case of a uniform electric field has been assumed.

An exception must be made in the case of Wagner,† who has discussed not a general macroscopic instability as described above, but local thermal instability arising from a microscopic crack or thread of impurity.

Recently the term "thermal instability" has occasionally been used to refer to cable failures, of whatever type, which have occurred as a result of the cables being passed through a series of heat cycles; that is to say, the term is used merely as a label to describe the general conditions relating to the circumstances of failure.‡ In view of the long history of the term used in its precise sense, its use for this purpose cannot be justified.

In the case of cables the non-uniform electric field and non-uniform temperature increase the difficulty of mathematical treatment. It is possible, however, to make an accurate approach to the matter by a quite simple step-by-step integration of the equations based on the continuity of electric and thermal flow. As in the rigid treatments, we assume a homogeneous dielectric in which the thermal resistivity and the electric permittivity are independent of temperature, and in which the D.L.A. is always sufficiently small not to affect appreciably the magnitude of the vectorial dielectric admittance.

We can consider a circular cable as in Fig. 2, having a conductor radius a, and a radius b over the dielectric. We can imagine the dielectric divided into a number of thin cylindrical shells by the cylinders r_1, r_2, r_3, etc.

When these shells are sufficiently thin, it becomes a reasonable approximation to suppose that the whole of the dielectric within, say, the first ring ar_1 is subjected to the condition of electric stress and temperature which actually exists on some intermediate circle at r'.

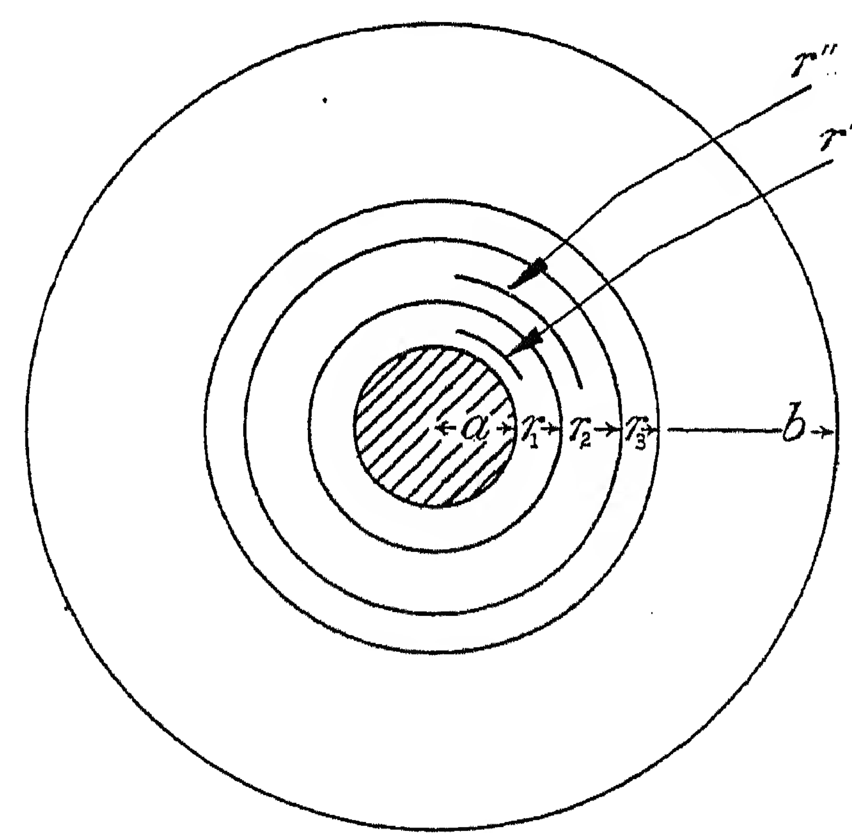


FIG. 2.

The integration must be started by assuming a temperature for the conductor. If we take for simplicity the case of no conductor-heating, this is also the temperature of the first ring ar_1. The electric stress at r' can be calculated from the voltage and dimensions of the cable. The stress at, and the temperature of, the ring are thus known. It is now necessary to refer to characteristic curves, such as those shown in Fig. 3, for the particular dielectric which will give the D.L.A. under these two conditions of stress and temperature. The D.L.A. and stress being known, the watts generated in the ring ar_1 can be calculated. This quantity of heat has to be transmitted from r' to the second intermediate circle r'', and the usual equations of thermal flow give the temperature-drop that will be caused by this transmission across the thermal resistance of the dielectric between r' and r''. The temperature of the second ring, r_1r_2, is thus ascertained; the stress is known; and the second ring can therefore be treated in exactly the same way. The only point of difference is that the heat to be transmitted from the second to the third ring is the sum of the heats calculated for the first and second rings. The process proceeds in this way, step by step, until the outermost ring is reached. The result of the whole pro-

* S. WHITEHEAD: *loc. cit.*
† K. W. WAGNER: *Transactions of the American I.E.E.*, 1922, vol. 41, p. 288.
‡ For example, M. KLEIN: "Kabeltechnik," p. 83.

cess is to show, for a given conductor temperature, what is the sheath temperature and the total dielectric energy generated, at which thermal and electric equilibrium will be reached.

The error due to the step-by-step approximation can be reduced to any desired value by increasing the number of rings. In practice it will be found that 10 rings give all the accuracy that is required. The work can be simplified by a number of devices. If the radii r_1, r_2, etc., are arranged in geometric proportion so that

$$\frac{r_1}{a} = \frac{r_2}{r_1} = \frac{r_3}{r_2}, \text{ etc.}$$

the capacitance and thermal resistance of all the rings become the same. If the dielectric is divided into n rings, and C_r, C_c, represent the capacitance of the rings and of the cable respectively and P_r, P_c, the thermal resistance of the rings and of the cable, then

$$C_r = nC_c$$
$$P_r = P_c(1/n)$$

In practice, the precision of the basic D.L.A./temperature/stress data of the dielectric does not justify the refinement of finding the intermediate circles r', r'', etc., to represent the ring, and sufficient accuracy is obtained by assuming the ring to take up the conditions existing at its inner or outer face. The practice that has been adopted is to take the inner face.

As a matter of fact, it is unnecessary for the radii to be calculated at all, since the expressions given above are independent of the actual values of r_1, r_2, etc. The only case when these need be calculated is when a curve of temperature distribution within the dielectric is required; but this does not provide information of any great interest or use. At the same time, however, it is necessary for the electric stress at the rings r_1, r_2, etc., to be calculated. This involves dividing the stress range S_a to S_b into 10 sections, in geometric proportion, which is practically the same as calculating the radii r_1, r_2, etc.

The method can most conveniently be followed by means of an example; a fully worked out case has therefore been included in Appendix 1.

The whole process is then repeated, starting from another assumed conductor temperature, and in this way sufficient points are worked out to enable a thermal-stability curve to be plotted, such as that shown in Fig. 4, which is discussed below.

In the description of the method given above, it was assumed that there was no conductor-heating. The case when the conductor is carrying current can, however, be worked out on the same lines without any further difficulty. The conductor is supposed to be carrying a definite current, and the number of watts per cm of the cable corresponding to this current, and to the resistance of the conductor at the temperature taken, is calculated. This amount of heat is then added to the dielectric loss at the first step, before the temperature-drop from the first step to the second step is calculated. The result of the calculation is a curve similar to that of Fig. 4, corresponding to a definite current flowing in the conductor.

This diagram, which is called the "thermal stability diagram," shows the watts generated in the dielectric in the equilibrium state for various values of sheath temperature. At a number of places on the curve corresponding values of the conductor temperature are marked. The difference between these values and the sheath temperature directly below the point shows the fall in temperature from conductor to sheath. As the abscissæ represent sheath temperatures, it is possible to draw on the curve a straight line corresponding to the external thermal resistance of, or dissipation from,

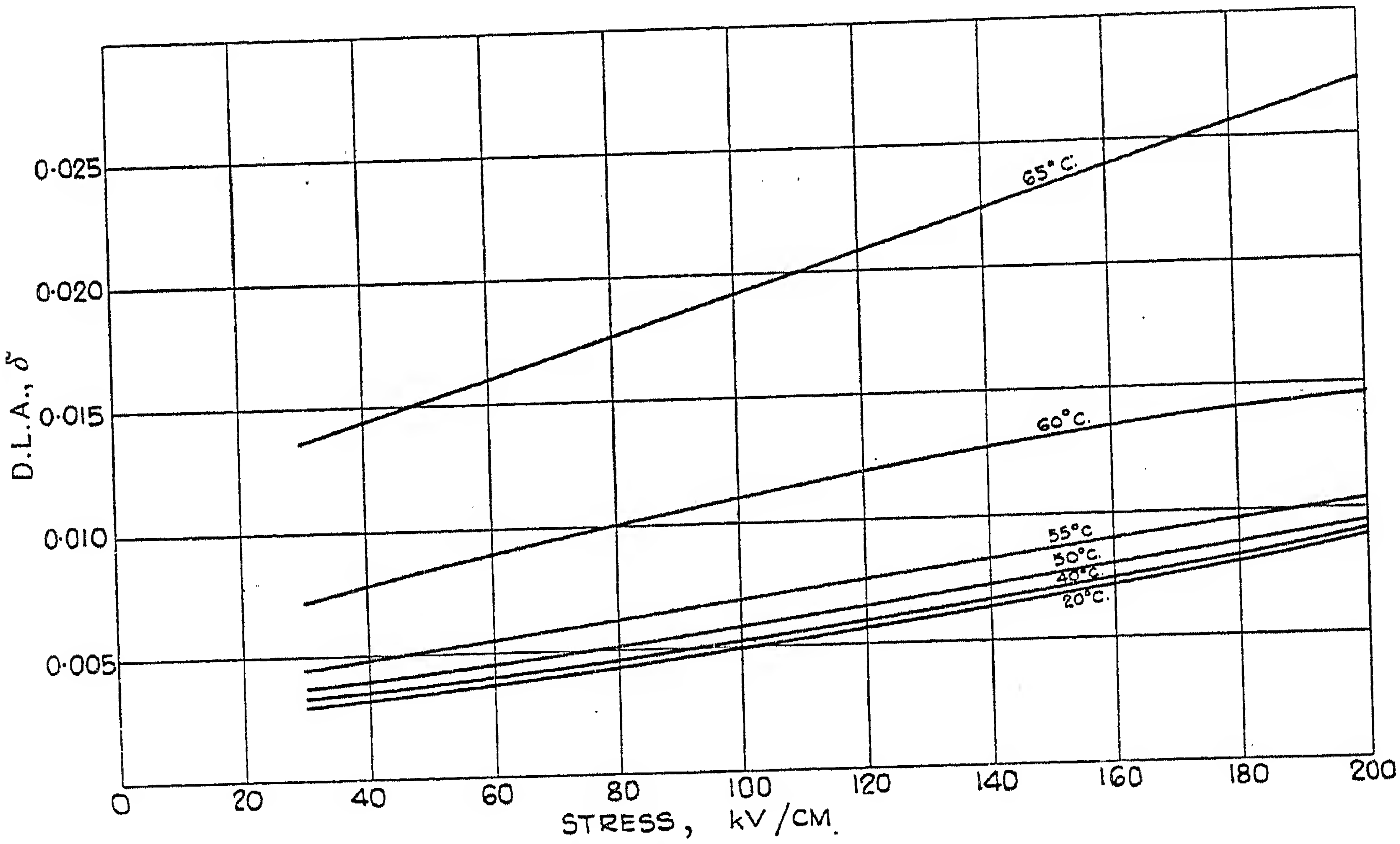


FIG. 3.—D.L.A./stress/temperature characteristics.

the cable. The intersection of these two lines shows the equilibrium point for the given conditions. Thus in the diagram the straight line shows a dissipation of 97 thermal ohms per cm from an ambient temperature of 20° C., and the corresponding equilibrium occurs at a sheath temperature of 23° C. It will be seen that the thermal-stability curve exhibits all possible steady-state working conditions of the cable, for the specified voltage and loading current; that is, it is the characteristic of that type of cable for a given kVA transmitted, and by application to it of the external resistance and ambient conditions we find that these conditions do or do not lead to a single stable operation point on the curve.

Plane Stress D.L.A.

Before proceeding to a discussion of the curves obtained in this way, it is necessary to notice a difficulty that arises. The calculations described above depend upon a knowledge of the characteristic D.L.A. of the dielectric as a function of the electric stress and the temperature. In working out the example given in Appendix 1, the family of curves reproduced in Fig. 3, showing values of D.L.A. against electric stress for various values of temperature, have been taken as the basis of the calculations. The difficulty is that with a cable dielectric it is not possible for a D.L.A./stress characteristic to be directly observed. The stress in the dielectric of a cable is not uniform, but varies inversely with the radius from the centre. When, therefore, the D.L.A. of a cable is measured, the result only provides a somewhat complicated mean, depending upon the true D.L.A./stress characteristic over the range of stresses existing in the cable at the voltage of the measurement. Measurements on plane condensers would overcome this difficulty, but it is a matter of the very greatest difficulty, if not impossible, to make an impregnated-paper dielectric in plane form so that D.L.A. measurements on the plane condenser can, with certainty, be taken as representative of cable dielectric. For discussions on this matter it has been found convenient to use the term "mass D.L.A." to describe measurements taken on cables, and "stress D.L.A." to refer to the deduced plane stress characteristic.

The question that arises is whether it is possible to deduce the stress-D.L.A. characteristic from the observed mass-D.L.A. curve. The matter obviously depends on whether the cable dielectric is uniform, that is to say, whether the D.L.A. is uniquely determined by the stress and the temperature. It might be expected that the mathematical analysis would provide a criterion for the uniformity of the dielectric. It is found, however, that this is not the case. Whatever the shape of the mass-D.L.A. curve, there can be found by suitable methods a corresponding stress-D.L.A. curve assuming uniform dielectric; and the result cannot, therefore, provide a criterion of uniformity. The question of uniformity is undoubtedly one of great difficulty in the case of cables exhibiting large amounts of gaseous ionization. Even in these cases, however, it appears from the agreement that has been obtained between experimental and calculated results that no great error is introduced by proceeding on the assumption of uniform dielectric. In the case of modern cables with negligible gaseous ionization, the dielectric can safely be taken as uniform.

Two methods of deducing the stress-D.L.A. characteristic from measurements of D.L.A. on a cable are described in Appendix 2. At the moment we are only concerned to note that such a transformation is possible.

It will be seen, however, that both the methods described are strictly only applicable to circular cables. It is probable that similar, though more involved, methods could be worked out for oval- or shaped-conductor cables. The variation of D.L.A. with stress, however, is small compared with the variation with temperature, and it appears, therefore, that little error will be introduced by treating the cables as circular cables, so far as the question of converting mass D.L.A. into stress D.L.A. is concerned.

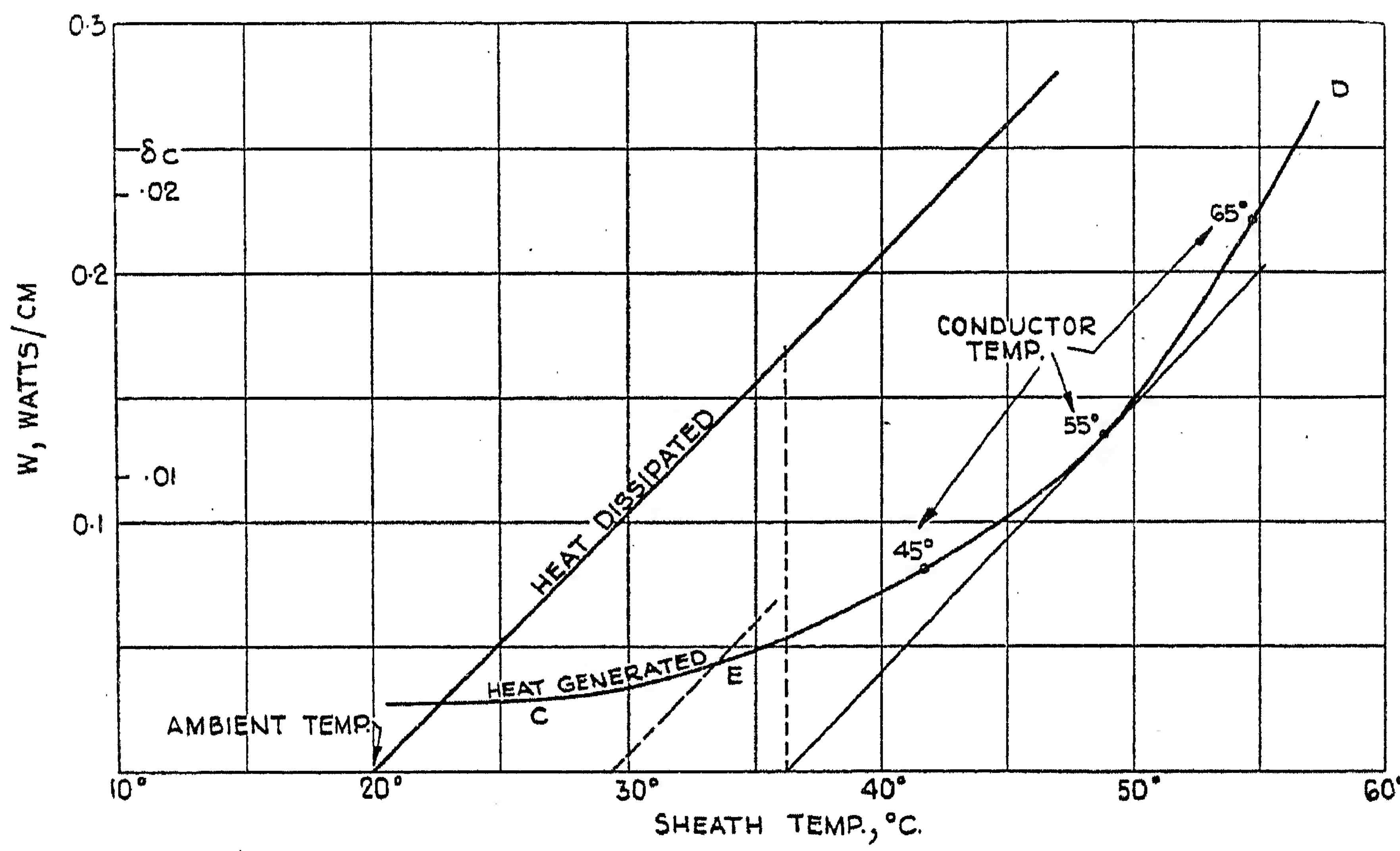


Fig. 4.—Thermal-stability diagram: 0·5 sq. in.; 0·7 in.-wall; 130 kV.

In this connection it is interesting to note that in the case when the D.L.A. is independent of the stress and varies only with the temperature, the whole calculation of the thermal-stability curve (Fig. 4) is independent of the dimensions or shape of the cable or dielectric. This really follows from the fact that the temperature-drop at each step is a function of the product $C_r P_r$; and for any given dielectric this product is constant whatever the size or shape of the portion of the dielectric considered.

The result is, therefore, that (apart from the secondary difficulty over the stress question) the step-by-step method of integration can be applied to non-circular cables of any shape. The only quantity that must be known is the capacitance or the thermal resistance of a cable of the particular cross-section. Moreover, when a thermal-instability curve has been calculated (subject to the limitations specified above), this curve is characteristic of any cable of whatever shape or size which is sustaining the voltage used in the calculation. It is this fact which brings out very suggestively the absolute character of the difficulties to be overcome in the design of cables for very high-voltage transmission. That is to say, given that a voltage V has to be sustained by the cable, then an increase in the dielectric wall does not primarily improve the position so far as thermal stability is concerned, but only secondarily so far as the D.L.A. is lowered at the lower working stresses. It will be seen from a later discussion in the paper that, so far as thermal instability is concerned, the main improvement resulting from an increase in the dielectric wall is that resulting from the lowering of the external thermal resistance which is thus obtained.

The Thermal-Stability Curve.

We can now return to a discussion of the thermal-stability curve (Fig. 4) when this has been calculated on the lines of the example set out in Appendix 1.

Experimentally, the data necessary for the calculation can be obtained as follows:—

A length of the cable is set up in the laboratory and arranged for D.L.A. measurements and for sheath heating by means of sheath current. Sheath-heating is applied, and arranged so that the sheath temperature is maintained steadily at a selected temperature for 1 or 2 hours until it can be assumed, or shown by conductor-temperature measurements, that the whole of the dielectric has been brought to the same temperature. Voltage is then applied and a curve of cable D.L.A. against voltage is taken as rapidly as possible. It is obvious that, as soon as the voltage is applied, there is a tendency for a thermal gradient to be established. As, however, the method requires that the D.L.A. measurements should refer to the particular temperature, it is obvious that the measurements must be completed before the voltage has seriously disturbed the uniformity of the temperature. For convenience, measurements taken in this way are termed "spot D.L.A."

This process is repeated at a sufficient number of temperatures to provide the mass-D.L.A./temperature/voltage curves, from which the calculations can proceed as described above.

It will, of course, be realized that the following examples do not necessarily represent the properties of the best modern cable dielectric. They have been chosen rather for the purpose of bringing out clearly the main features of thermal instability.

For a particular cable with a 0·5-sq. in. conductor and a 0·7-in. wall, the D.L.A./temperature/stress curves calculated from the D.L.A./temperature/voltage curves are shown in Fig. 3.

In considering these curves, it must be remembered that the D.L.A. figures have been obtained with the cable arranged so that the whole of the dielectric has been brought up to the temperature to which the measurement is referred. The D.L.A./voltage characteristic is often exhibited by means of measurements taken on a cable with conductor-heating only, in which case, of course, only the inner portions of the dielectric are brought up to the temperature of the measurements. It is to be expected, therefore, that D.L.A. measurements taken with sheath-heating or oven-heating will be substantially higher than those obtained with conductor-heating.

From these data the thermal-stability curve shown at CD in Fig. 4 has been calculated. This curve shows the watts generated in the dielectric plotted against the sheath temperature when the cable is operated at 130 kV. At certain points in the curve are marked the corresponding values of conductor temperature. The thermal dissipation from the cable as erected in the laboratory was found to be 97 thermal ohms (° C. per watt) per cm. This dissipation line has been drawn on the graph, assuming an ambient temperature of 20° C. It will be seen that the two curves intersect at a temperature of 23° C., which represents the equilibrium state under these conditions.

Now consider the case when sheath-heating current is applied to the cable. Let the current be adjusted to correspond to a sheath-heating of, say, 0·1 watt per cm. The conditions can now be represented graphically by raising the heat-generated curve by 0·1 watt per cm, or more conveniently by lowering the heat-dissipated line the same amount. It will be seen that this is, in fact, equivalent to raising the ambient temperature by $97 \times 0 \cdot 1 = 9 \cdot 7$ degrees, which would give a stable operating point at about 33° C., as shown at E. Thus by moving the heat-dissipated line to the right, it will be found that the critical thermal-instability point when the line is tangential to the curve occurs at a conductor temperature of 55° C. and a sheath temperature of 49° C. The corresponding value of the ambient temperature is 36° C., and the vertical through this point shows that this requires a sheath heat-generation of 0·17 watt per cm if the laboratory is actually at 20° C. At the moment of instability the dielectric heat-generation amounts to 0·13 watt per cm, corresponding to a cable D.L.A. $\delta_c = 0 \cdot 0115$.

These calculations were confirmed experimentally by applying to the sheath sufficient heating current to cause the temperature to rise to 36° C. The current was continuously adjusted so as to correct for variations in the true ambient temperature. The sheath temperature was observed by thermometers or thermocouples attached to the sheath at frequent intervals. The test voltage of 130 kV was then maintained on the cable. The temperature of the sheath rose steadily but very slowly.

This slow rise is to be expected from the flat "intersection" of the generated and dissipated lines in Fig. 4. When, however, the average of the thermocouples reached 48° C., two thermocouples began to rise in temperature rapidly. At a maximum sheath temperature of 58° C. the voltage and current were shut off and the

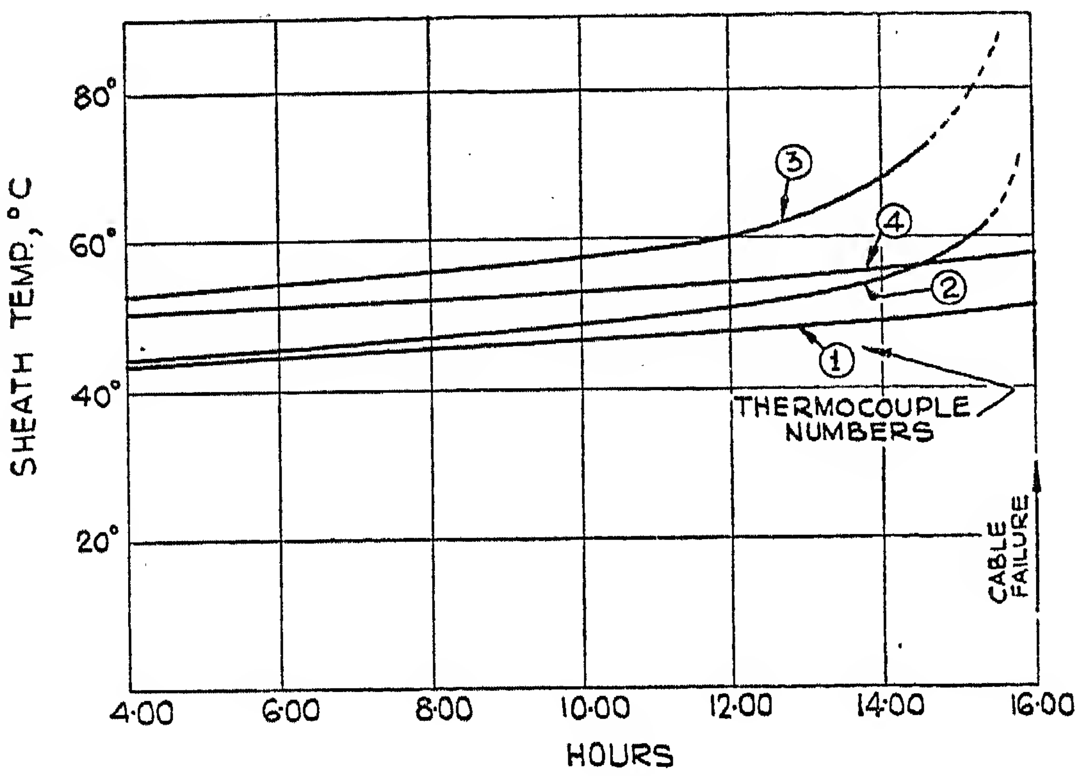


FIG. 5.—Sheath temperatures approaching thermal instability; experimentally determined.

cable was allowed to cool to 38° C., when they were reapplied. It was then found that the cable continued to run for a further 40 hours before the hot spot reappeared. It was clear, therefore, that the first hot spot had not caused any permanent alteration to the dielectric and that it could not have been due to an embryo failure of the ionization type. An incipient tracking breakdown will cause a hot spot, but this is always accompanied by perceptible damage to the dielectric, and the hot spot immediately reappears, however long the cable is rested. This preliminary result has been abundantly confirmed by many later observations that the dielectric can be allowed to go into thermal instability, rising even to local sheath temperatures of 110° C., but that if the voltage is cut off a short time before failure the dielectric is found to be undamaged.

The same voltage and sheath current were reapplied, and again, on reaching 50° C., the same two thermocouples began to rise rapidly, as shown in Fig. 5. The conditions were not disturbed and the cable was allowed to go to failure. The final sheath temperatures were not observed in this case, but in other cases sheath temperatures up to 110° C. have been noted.

It will be seen, therefore, that thermal-instability calculations of this kind can be relied upon to predict with accuracy the thermal behaviour of cables. The details of the post-mortem examination of this cable are reserved for a general discussion of the post-mortem characteristics of thermal-instability failures later in the paper.

INTERNAL AND EXTERNAL INSTABILITY.

It will be seen from Fig. 4 that the instability point is largely controlled by the slope of the external-resistance line and that, therefore, the thermal instability arises mainly from the external resistance to dissipation of heat from the sheath, rather than from resistance to the conduction of heat from the interior dielectric to the outside. This has been termed "external instability." The question arises whether instability can occur in the internal portions of the dielectric owing to the difficulty of transferring heat through the dielectric wall, and without throwing the cable as a whole into instability. This can conveniently be called "internal instability." Light has been thrown on this matter by instability calculations for a cable of the same dimensions, and of nearly the same D.L.A./temperature characteristic, as that of Fig. 3. The instability curves for a number of different voltages are shown in Fig. 6. It will be seen

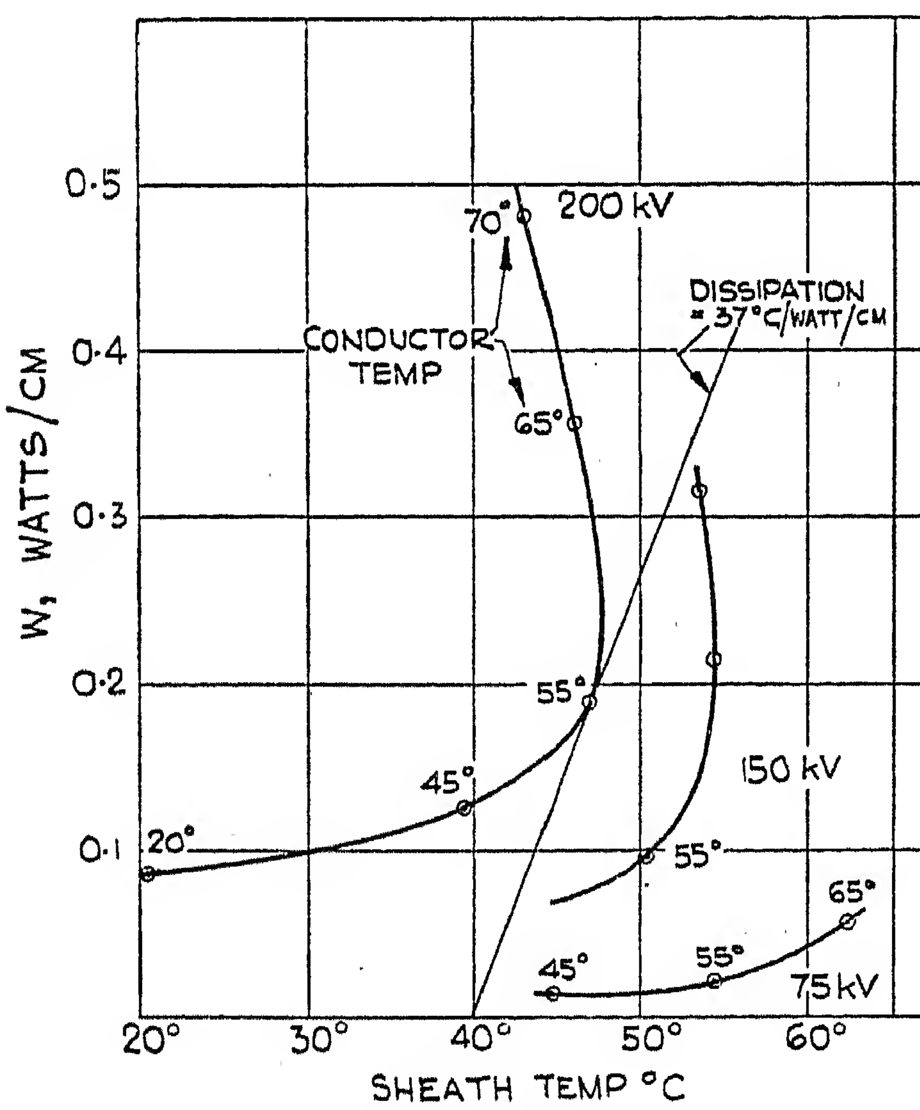


FIG. 6.—Instability curves: 0·5 sq. in.; 0·7-in. wall; no conductor current.

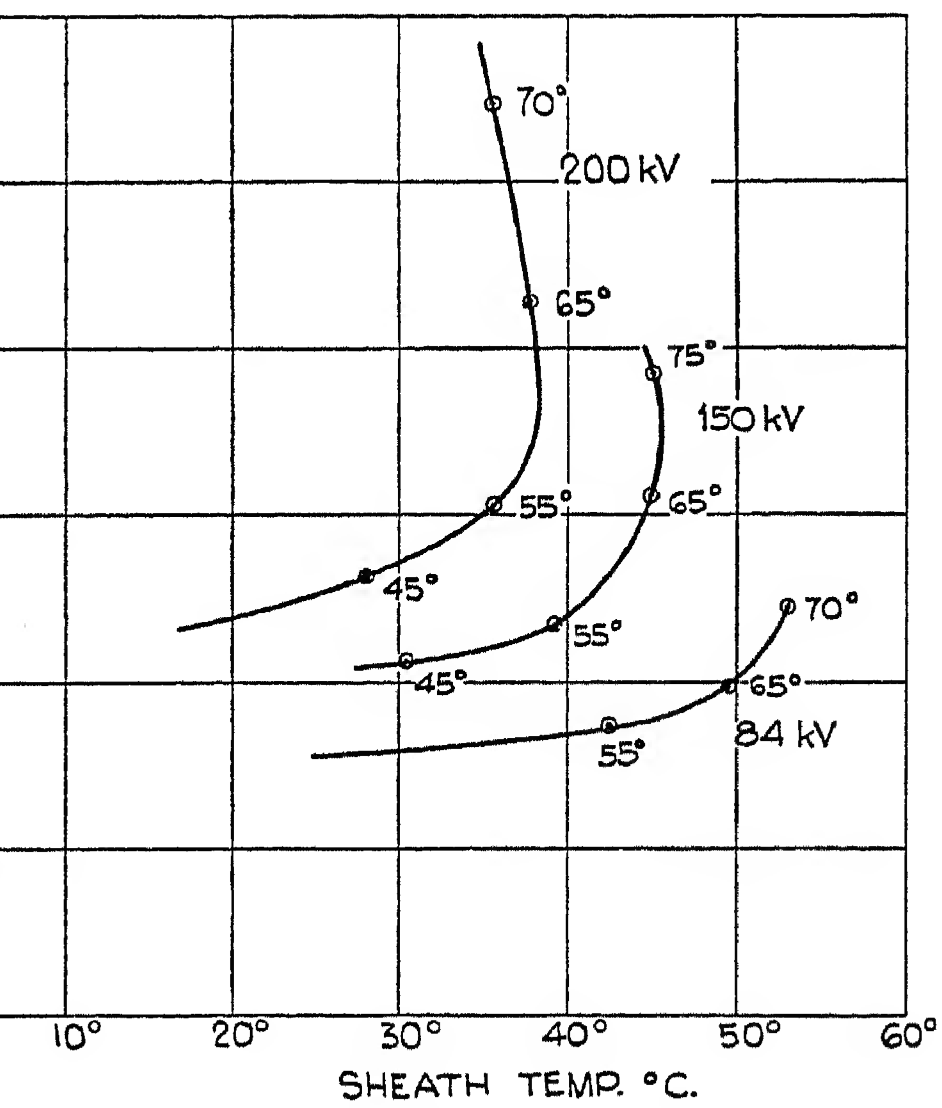


FIG. 7.—Instability curves: 0·5 sq. in.; 0·7-in. wall; 500 amperes conductor current.

that at 75 kV the curve has the same general characteristics as those discussed under Fig. 4. At 150 kV, however, the curve rises vertically at a sheath temperature of 54° C., while at 200 kV the curve actually bends back and returns to lower sheath temperatures. If we take the 200-kV curve, when the conductor is at 70° C. this means that the heat generated in the dielectric cannot be transmitted through the dielectric wall unless the sheath is kept down to a temperature of 43° C. It is clear, however, that even if the sheath temperature is held down by forced cooling, the internal portions of the dielectric will go into instability as soon as a conductor temperature of about 57° C. is exceeded.

This was tested experimentally on a cable which was known to have an asymptotic value on its voltage/life curve considerably in excess of 200 kV; that is to say, 200 kV could safely be applied for periods of 300 hours or more at ordinary ambient temperatures without any risk

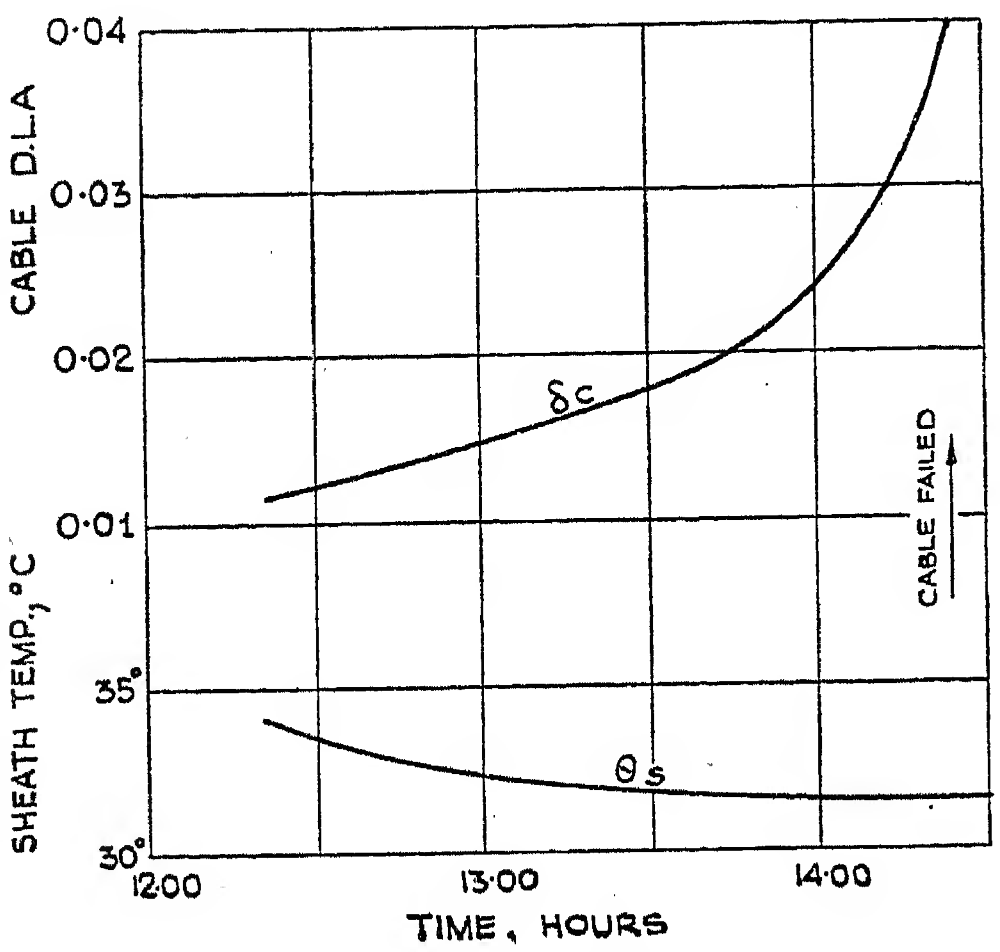


Fig. 8.—Breakdown of cable by internal instability: 0·5 sq. in.; 0·7-in. wall; 200 kV.

of damaging the dielectric. The cable was arranged so as to obtain the maximum dissipation from the sheath—actually an external thermal resistance of 37 deg. C. per watt per cm of cable. The cable was raised by sheath-heating without voltage to the region of 40° C., when the heating current was shut off and a voltage of 200 kV applied. After one or two trials it was found that, when the current was shut off at a temperature of 38° C., the sheath temperature continued to fall slowly while, at the same time, however, the cable D.L.A. (δ_c) rose steadily, showing that the conductor and inner dielectric were rising in temperature, in spite of the fall of sheath temperature. The curves of δ_c and sheath temperature are shown in Fig. 8. This cable showed the same post-mortem features as are characteristic of thermal-instability failures.

Effect of Conductor Current.

The effect of conductor current can conveniently be exhibited by showing the thermal-instability curves for the same cable, but with a conductor current of 500 amperes, that is to say, 1 000 amperes per sq. in.

A number of such curves are shown in Fig. 7, which, for convenience, is plotted by the side of Fig. 6 and to the same vertical scale. The effect of variations of voltage and conductor current can conveniently be seen by considering the effect on the "instability ambient temperature" with a standard external thermal resistance or dissipation of, say, 97 thermal ohms (deg. C. per watt) per cm of cable. By this is meant the ambient temperature which will result in the cable being thrown into instability by the voltage and conductor current in question. The margin between the instability ambient temperature and the actual ambient temperature is, of course, a measure of the margin of safety under which the cable is operating. The curves of instability ambient temperature for this particular cable are shown in Fig. 9.

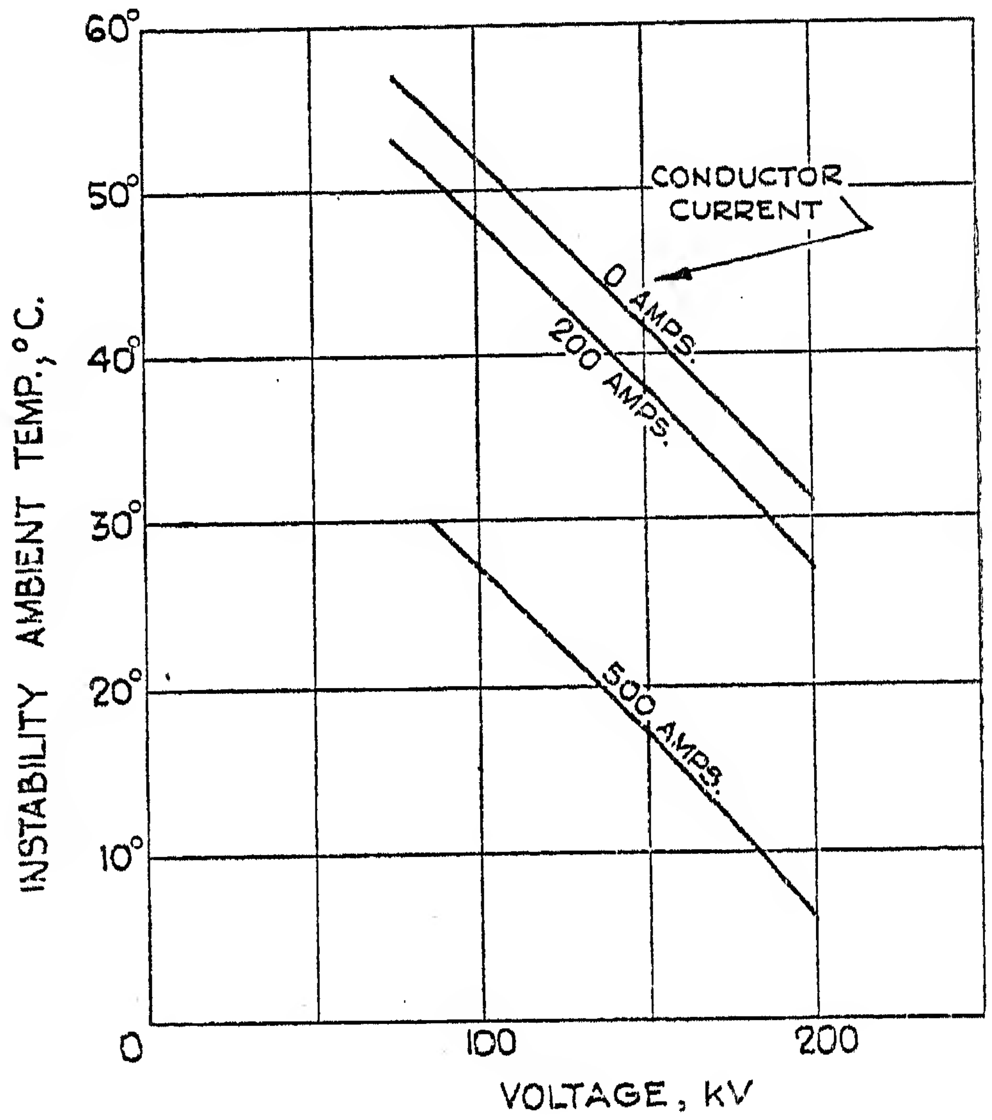


Fig. 9.—Instability ambient temperatures: 0·5 sq. in.; 0·7-in. wall.

Cables under Service Conditions.

In the examples that have been discussed, which were, as a matter of fact, chosen for convenience of laboratory demonstration, the voltages that have been considered are higher than those occurring in present-day cable-engineering practice. The question arises whether considerations of this kind are of importance for cables under present-day service conditions.

It is quite easy for a cable, of the dimensions already assumed in the examples, to be built which will operate on a 132-kV system with no risk of breakdown of the tracking type. It must, however, be realized that the external thermal resistances of cables under service conditions are very considerably higher than the figure of approximately 100 thermal ohms assumed in the examples. The factors contributing to this increase in thermal resistance are the depth of laying which is sometimes found necessary, poor local thermal conductivity of the soil, the effect of grouping 3 single-conductor cables to form a 3-phase feeder, and the proximity* factor of other feeders. As a result, it is

* It is immaterial whether the proximity factor of other feeders is treated as an increase of ambient temperature or an increase of external thermal resistance.

found as a matter of experience that such cables in practice will frequently have an external thermal resistance as high as 550 thermal ohms; and cases have actually occurred where the figure has risen to 972 thermal ohms. In addition, in urban districts the normal summer soil-temperature rises to 18° C. If, now, a dissipation line of 500 thermal ohms is laid out from an ambient temperature of 18° C. on to the lower-voltage curves of Figs. 6 and 7, it will be seen that for cables above 66 kV the question of thermal instability cannot be dismissed without consideration.

In the case of these high external thermal resistances, the method of approach described above, although accurate, is not very convenient because the emphasis is placed on the thermal conditions when the cable is carrying a definite current. In practice, what is required is to know the thermal state at a given conductor temperature, and what conductor current can be carried in this state.

Where the external thermal resistance of the cable is known, a convenient method of carrying out the calculations is to start the step-by-step integration at the sheath instead of at the conductor. A thermal flow across the sheath is arbitrarily assumed, and this, in conjunction with the known external thermal resistance, determines the temperature of the sheath. This provides all the information necessary for the integration to be started. When the integration reaches the conductor, there is a residual heat generation which can be utilized as current-carrying capacity for the particular size of conductor concerned. By carrying through a number of these integrations, it is possible for a curve to be plotted showing current-carrying capacity against sheath or copper temperature. This curve will pass through a maximum value, thus determining directly the current and temperature at which the cable becomes thermally unstable for the particular conditions of external thermal resistance taken.

When the external thermal resistance is very high, however, it becomes possible to use a simpler approximation. In these cases the fall of temperature in the cable itself is small, so that it becomes a reasonable approximation to utilize the thermal-stability curve calculated with no conductor current; this represents, in fact, a limiting case, and, as will be seen from the discussion below, is such that the calculated current-carrying capacity is slightly on the safe side.

We can consider a 132-kV cable and take the 84-kV curve from Fig. 6. This allows a 10 per cent voltage margin over working conditions. This curve is re-plotted in Fig. 10. Now consider this in relation to a moderately high external thermal resistance of 300 thermal ohms and an ambient temperature of 18° C. This dissipation line has been shown in the figure. The intercept AB shows that, at a conductor temperature of 65° C., 0·07 watt is available for conductor-heating. This value actually refers to dissipation from the sheath. As the heat will be generated in the conductor, it is necessary to allow for the additional 77 thermal ohms of cable thermal resistance. When, therefore, 0·07 is multiplied by the factor 300/377 we obtain 0·0519 watt conductor heating, corresponding to 289 amperes on a 0·5-sq. in. conductor. The effect of this conductor current on the thermal-stability diagram can be approximately obtained by raising everywhere by an amount 0·07 watt the curved line of heat generated. This raised line has been shown dotted. The intersection at B shows that equilibrium will be obtained at this state between the heat generated and the heat dissipated; but the fact that the heat-generated line is rising more steeply than the heat-dissipated line shows that it is actually an *unstable* equilibrium. The difficulty is, of course, that we have arrived at the right-hand intercept B between the heat-generated and heat-dissipated lines, instead of the left-hand intercept C.

The question will be raised: "What is the relation of the results obtained in this way to the results obtained by the ordinary calculations of current-carrying capacity?"

In the normal calculations, allowance is made for the dielectric loss in one of two ways. According to a well-known result, if the D.L.A. throughout the cable wall is uniform, then the temperature-drop in the cable due to the dielectric loss will be half the drop caused by the same total loss concentrated at the conductor. It is a common practice, therefore, to assume some round figure for the D.L.A. (although, of course, there can be no accurate knowledge about the mean D.L.A. under the

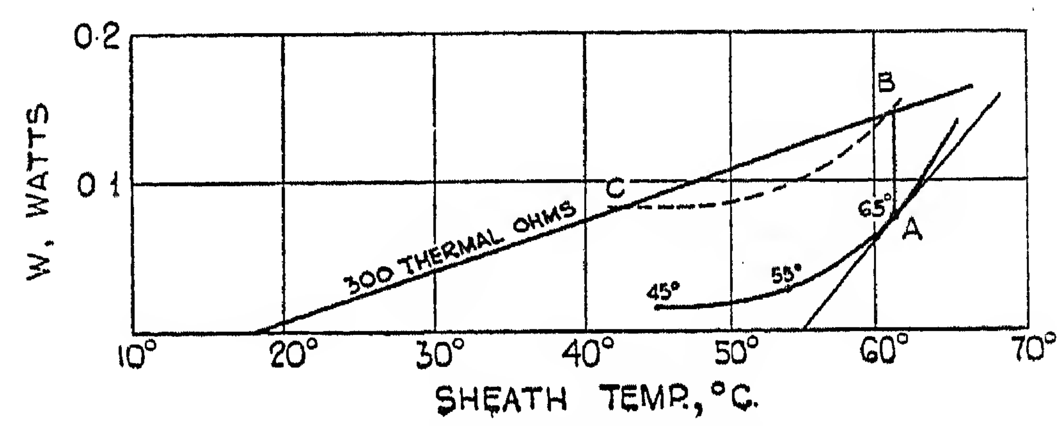


FIG. 10.—Current-carrying capacity of 0·5-sq. in. 132-kV cable.

particular conditions of the calculation) and to assume half the corresponding dielectric loss concentrated at the conductor. Sometimes, as a safeguard, the whole of the dielectric loss is assumed to be concentrated at the conductor. If, now, calculations on the latter basis are carried out for the above cable, a result is obtained which is very nearly the same as that given above, and in the absence of a stability diagram the cable might be passed for a current of 289 amperes at a conductor temperature of 65° C., although this would certainly involve a thermal-instability failure. Actually, if a current of 289 amperes is applied to the cable, the latter will come into equilibrium at the intersection C (Fig. 10), that is to say, at a conductor temperature of 43° C. The maximum intercept, namely 0·094 watt, which occurs between the two lines at a sheath temperature of 54° C., shows that at this temperature the current-carrying capacity is actually 335 amperes, although, of course, it would, in practice, be necessary to allow a margin on this figure for contingencies. Actually, therefore, the straightforward balance calculations have failed to disclose the true situation in two respects. They do not disclose that an operating conductor temperature of 65° C. necessarily involves a thermally unstable state, and secondly, that the maximum current-carrying capacity of 335 amperes is obtained at a conductor temperature of 55° C.

It will be seen that the critical matter is whether the tangent at A is steeper or less steep than the dissipation

line CB. If it is steeper than the equilibrium point, B will be unstable. In the present example, the tangent at A corresponds to a thermal resistance of 88 ohms. The above result can therefore be expressed by saying that in this case, when the external thermal resistance is less than 88 thermal ohms, ordinary thermal-balance calculations will determine an equilibrium state that is stable, but if the external resistance exceeds 88 thermal ohms the calculated equilibrium will be unstable. It will be seen, therefore, that the tangent at A provides a very convenient criterion for the sufficiency or insufficiency of normal current-carrying calculations. The matter can be usefully illustrated by Fig. 11, which shows on the left-hand side a small current-carrying capacity which is stable, and on the right-hand side a large current-carrying capacity which is unstable.

It is of interest that so well-established an authority as Hochstadter, by using different methods, has arrived at conclusions which are not supported when the same subject matter is considered by the methods discussed here. In an article, "The Insulation of the H.T. Cable,"* he has discussed the thermal stability of a particular cable under a very high test stress of 350 kV per cm, and he arrives at the conclusion that there is no risk of thermal instability. It can be shown, however, when the data provided in Hochstadter's paper itself are treated by the present methods, that thermal instability is certainly to be expected when the cable carries any reasonable current.

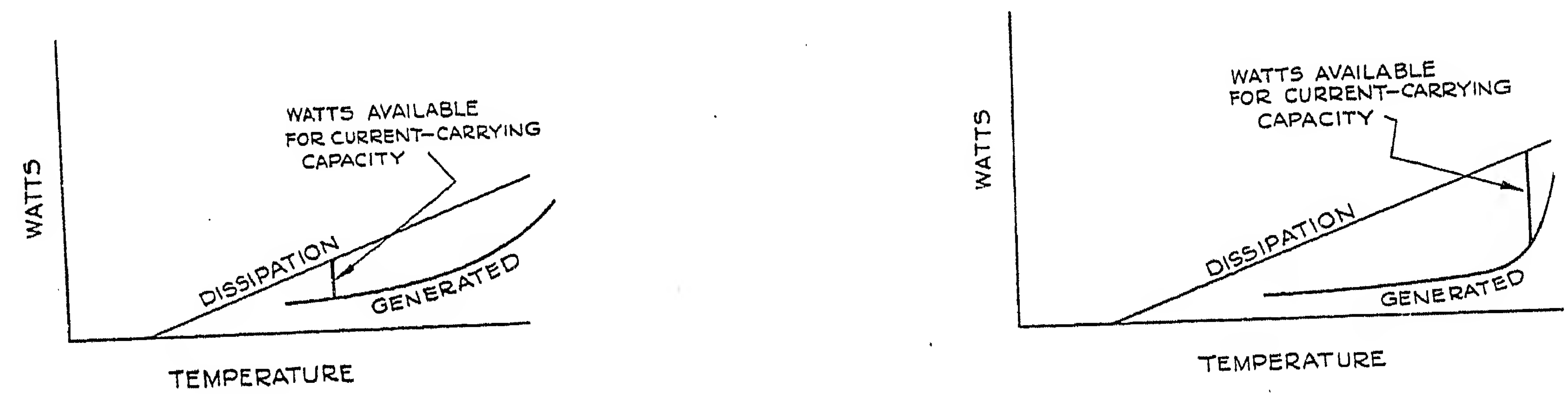


FIG. 11.—Examples of stable and unstable equilibria.

POST-MORTEM CHARACTERISTICS.

A thermal-instability failure is very regular in its general appearance. A hole, varying in size from about 3 mm diameter to about 1 cm × ½ cm, runs straight through the dielectric from the outer electrode to the conductor. The edge of the hole is surrounded by a fringe of charred paper. As the papers are unwrapped from the cable, there may be an appearance of dryness surrounding the ring of charred paper, or there may sometimes be an area of scorched paper and compound extending to about 5 cm on each side of the fault, giving a characteristic, even, brown colour. There is a complete absence of treeing, or of wax deposit, even when a test for wax is made by the magenta dye method.† It will, of course, be realized that the magenta test may sometimes show up waxing due to other actions which may have been going on in the dielectric; but the waxing is certainly not an essential feature of thermal-instability failures. Photographs of characteristic thermal-instability failures and of individual papers are reproduced in Figs. 12, 13, and 14 (see Plates 3 and 4, between pages 112 and 113).

With the particular cable dielectric used during this work it has been found that the smell from the cable sample, as it is being dissected during examination, provides an easy and certain clue to the type of failure that has taken place. This dielectric is of the ordinary solid type, that is to say, paper impregnated with a resin-compound mixture. Three distinct kinds of smell can be distinguished:—

(*a*) When breakdown by the tracking mechanism reaches the stage of producing treeing or carbonization tracks, it is always accompanied by the rank, acrid smell (distinct from the resinous smell of healthy compound) which is well known as a characteristic of cable breakdown or deterioration. This is probably associated with the organic acids produced by pyrolysis of the cable compound.

(*b*) Void spaces within the dielectric which are remote from either the inner or the outer electrode can be subjected to heavy ionization discharge for long periods without the production of any carbon. This action is particularly pronounced in a dielectric which has become very dry on account of drainage or other reasons. The gaseous ionization results in condensation* of the compound into the well-known wax, and this is accompanied by the peculiar, musty smell of dry mice-ridden stores, which is normally accepted as characteristic of nitrogenous compounds. It has not been found possible, however, to isolate any nitrogenous compound, and the matter is still under investigation.

(*c*) Where thermal instability or failure occurs in a well-impregnated dielectric, it is normally accompanied by a smell similar to that of burnt sugar or toffee, which is characteristic of the decomposition of carbohydrates; and is, therefore, presumably attributable to decomposition of the paper.

In many instances of thermal-instability failure, it is found that, when the innermost paper is unwrapped from the conductor, the free compound lying between the paper and the strand spaces of the conductor is of a very dark, nearly black, colour. This appearance is likely to be mistaken for compound discoloured with free carbon, which is frequently found to be flowing longitudinally from the actual fault up the strand spaces, doubtless as a result of the explosive character of the failure. On close examination, however, it will be found that the

* *Elektrotechnik und Maschinenbau*, 1933, vol. 51, p. 218.
† D. M. ROBINSON: *loc. cit.*

* This is frequently termed "polymerization," but, as the action is always accompanied by the evolution of hydrogen and volatile hydrocarbons, it can only strictly be termed "condensation."

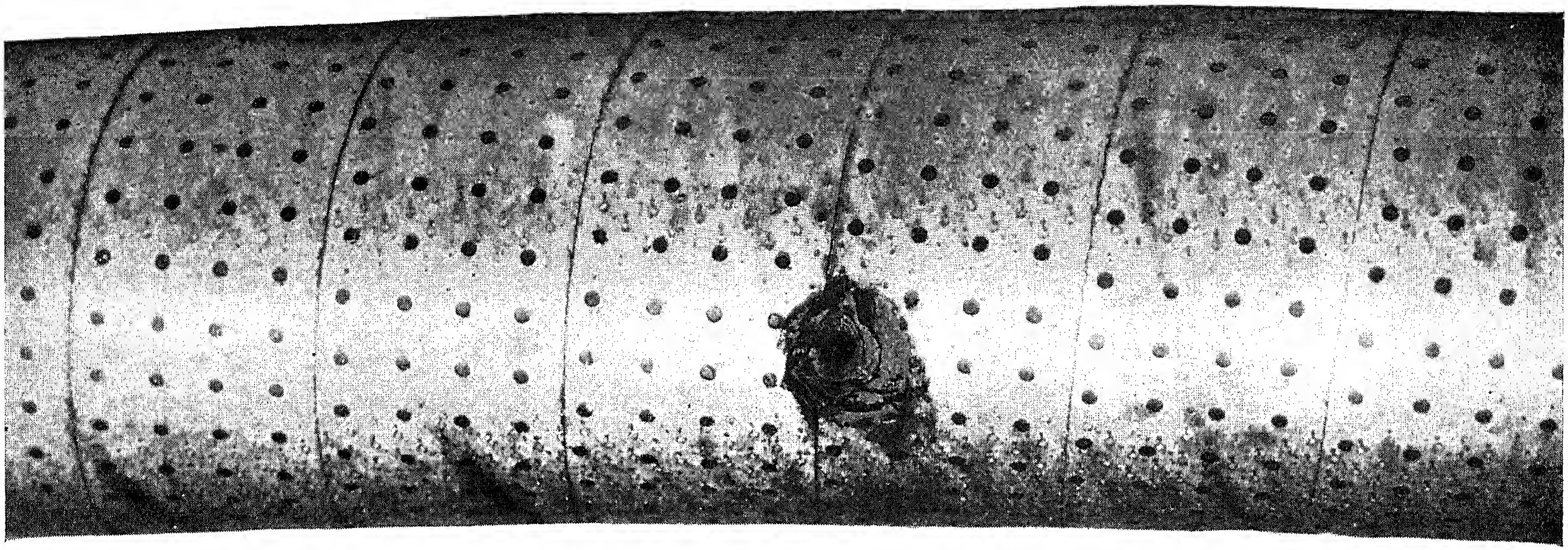


FIG. 12.—Characteristic thermal-instability failure. View of outside of metallized paper.

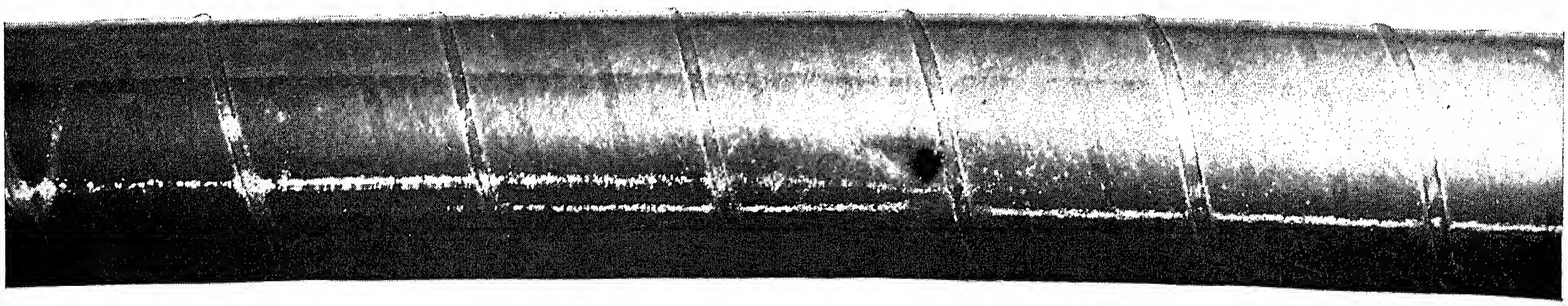
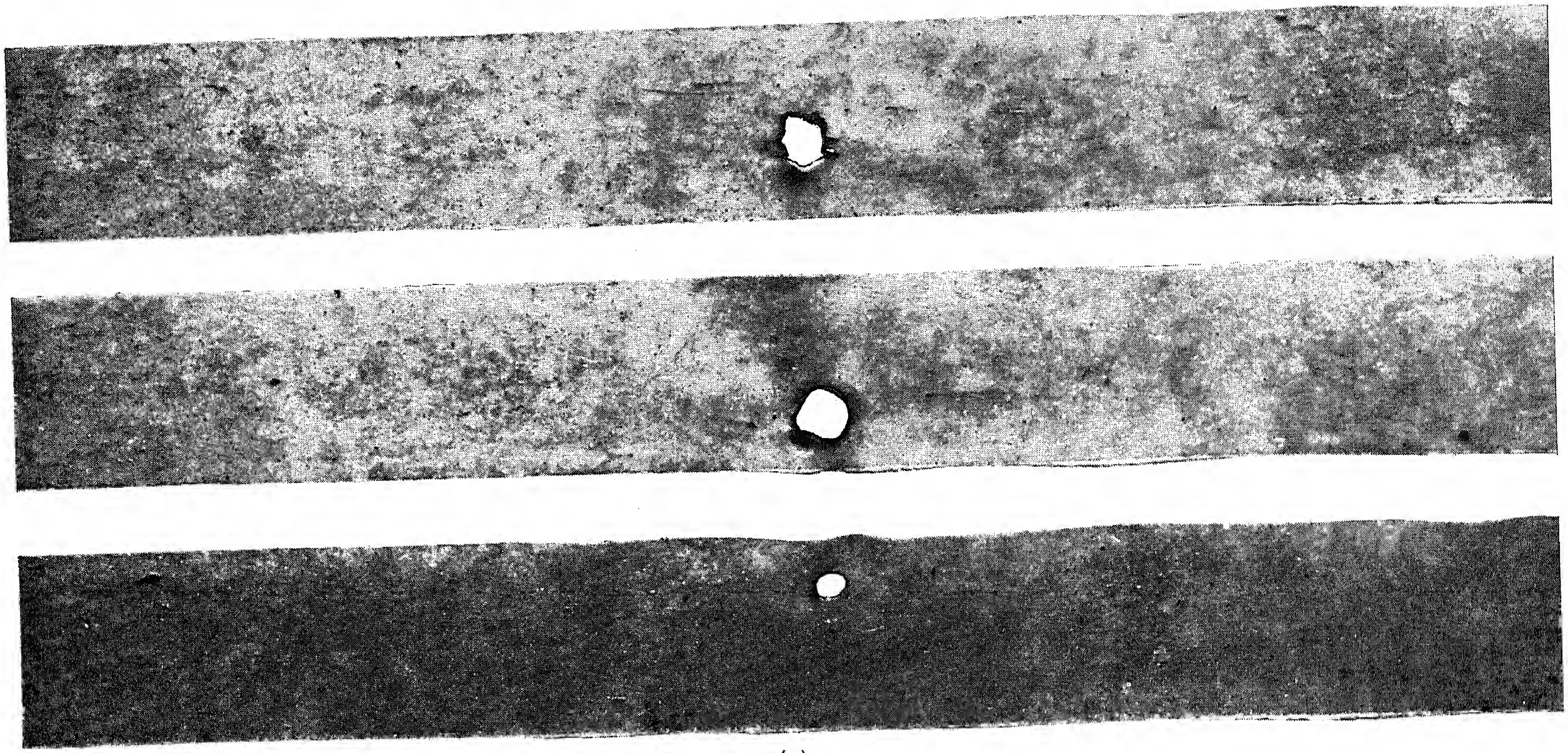
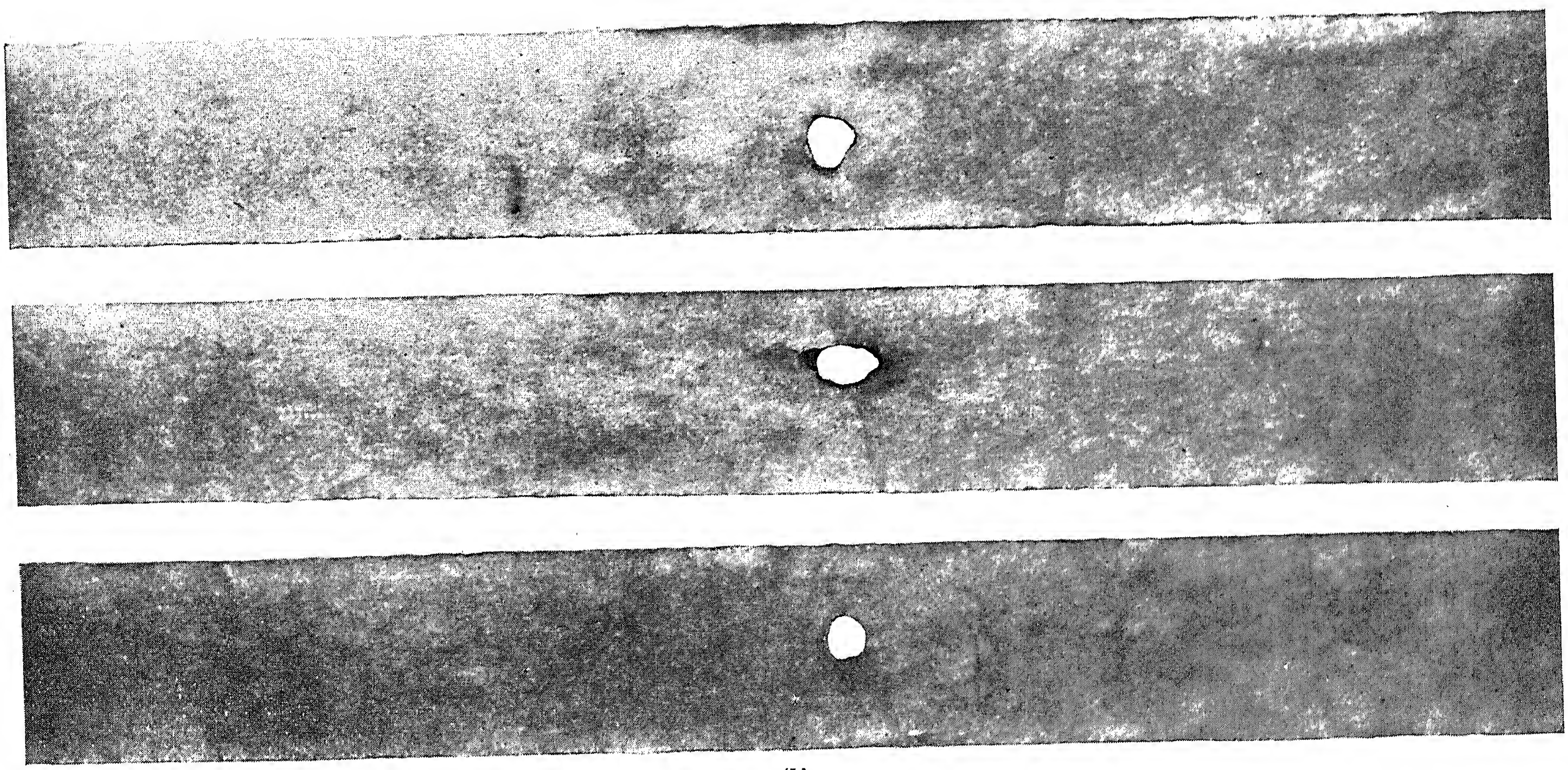


FIG. 13.—Characteristic thermal-instability failure. View at 30 papers from the outside.

Plate 4.



(a)



(b)

FIG. 14.—Characteristic papers from thermal-instability failure.

(a) Undyed.
(b) Papers compound-extracted and magenta-dyed; showing complete absence of waxing and treeing.

discoloured compound occurs uniformly round the conductor, and over a considerably longer distance than when the compound contains carbon. On following this matter up, it has provided a clue as to the maximum temperature reached by the conductor immediately preceding an instability failure. The question of maximum sheath temperature has already been mentioned on page 109.

On close examination of the paper taken from one of these regions of discoloured compound, a faint sheen of copper deposit could be seen on both the inner and outer faces of the paper. The discoloured compound was found to contain not carbon but copper rosinate. The question was considered, therefore, what kind of action could be proceeding in the dielectric which could result in the first place in the production of copper rosinate in the compound, followed by the precipitation of copper on the paper.

It was at first anticipated that such results could be produced by the effect of an electric discharge, but no satisfactory results could be obtained from this line of attack. It was then considered whether heat alone could produce the effect. It is known that if, for any reason, the copper has a superficial coating of copper oxide, then, in the event of this being in contact with resin compound, a solution of copper rosinate will be formed at a temperature of 100–150° C. The question was therefore investigated whether copper is deposited from a solution of copper rosinate in compound at temperatures above this. It was found that copper is deposited from copper-rosinate solution at a temperature above 180° C., and that at temperatures of 200° C. the whole of the copper is deposited within 5 minutes. It is also easy to show that normal cable paper can be subjected to a temperature of 200° C. for 5 minutes without affecting in any way its appearance or its mechanical or handling properties, at any rate so far as these are tested by hand during a cable examination. It therefore appears that after a cable has been thrown into thermal instability the temperature will rise to more than 200° C. before electric rupture of the dielectric occurs.

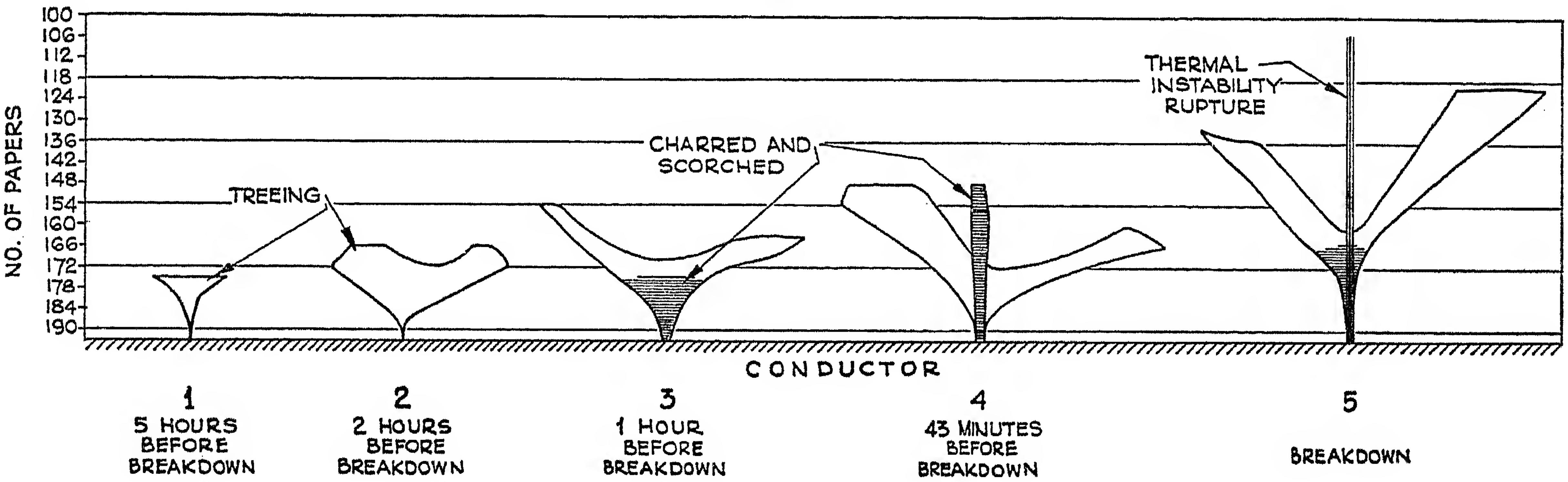


Fig. 15.—Deterioration diagrams.

Transition from Ionization Breakdown to Thermal Instability.

In the examination of the quality of a cable, the determination of the voltage/time-to-breakdown (V.T.B.) curve forms an important part. Short lengths of the cable are tested at voltages in the region of 3–4 times working voltage with the object of producing breakdown over the range of from, say, 10 to 200 hours. In carrying out this work, a practice has been standardized of equipping every length of cable tested, with thermocouples attached to the sheath of the cable at intervals of not more than 2 ft. These thermocouples are kept under continuous observation by means of a thread recorder equipped with a specially developed rotary switch, which connects the thermocouples in turn to the thread recorder at 1-minute intervals. The thread recorder therefore provides a repeated pattern of dots, each pattern being, in effect, a curve of the temperature distribution along the cable. It has been found that in this way advance indication of a cable breakdown can be obtained up to periods of 10 hours before the actual failure. The interval between the appearance of local heating and the final failure, which is termed the "breaking time," is fairly regular, so that for given conditions it is possible for the time of actual failure to be predicted once the hot spot has appeared. This knowledge has enabled incipient cable faults to be arrested at various stages of failure. Every failure is subjected to a post-mortem examination, and careful records over a great number of tests have enabled the course of cable failure to be followed and analysed at successive stages.*

In Fig. 15 is shown a series of 5 deterioration diagrams taken progressively nearer to the time of actual cable failure. The unshaded area enclosed in the diagram shows the limits of ordinary cable treeing. It will be observed that in the first case, which was arrested 5 hours before failure, there is a small triangular patch of treeing, starting from the conductor in the manner that Robinson† has described. In case 2, which was arrested 2 hours before failure, it will be seen that the treeing mechanism had begun to branch out in two horn-like tracks, and in accordance with the Robinson mechanism the angles of these tracks are largely governed by the width, thickness, and overlay of the cable papers. In case 3, which was arrested 1 hour before failure, it was found that the horns had progressed farther, but that in addition, in the actual crutch of the horns, as shown by the shaded region, so much heat had been developed by the treeing deteriora-

* The author is indebted to Mr. A. F. C. Adye for assistance in carrying out this work. Mr. Adye first observed the transition mechanism described here.
† D. M. Robinson: *loc. cit.*

tion that the paper had actually become scorched and charred. Case 4, taken 43 minutes before failure, shows the scorched and charred region developing on its own direct path outwards through the dielectric. The paper in this shaded region has very largely the appearance of paper surrounding a failure by thermal instability. It is quite clear, in fact, that what is happening is that the additional heat generated by the treeing deterioration is becoming so great that the central region of the fault is being thrown into thermal instability. No. 5, the last of the series, was taken actually from a cable failure. It shows the two horns of the treeing deterioration well developed, the central region of scorched and charred paper, and, finally, the direct piercing of the dielectric wall by rupture, characteristic of thermal instability.

It will be observed from the last diagram that, at the moment when the failure is precipitated into thermal instability, the treeing deterioration has penetrated only 70 layers of paper out of the 190 layers which constitute the dielectric wall. It is found that this penetration by the treeing horns at the transitional point between tracking breakdown and thermal instability behaves with considerable regularity for cables of different dimensions and under different test conditions. A study of the transition point between the two main types of breakdown as measured by this penetration is now in progress and appears likely to provide results of considerable interest.

Acknowledgments.

The author's acknowledgments are due to Callender's Cable and Construction Co., Ltd., for permission to publish this paper. He is also particularly indebted to Dr. D. M. Robinson and other colleagues, in addition to those who have been mentioned in connection with particular results, for frequent and valuable discussions that have taken place during the progress of the work.

APPENDIX 1.

Step-by-Step Integration.

$$a = 1\cdot 176 \text{ cm};\ b = 2\cdot 95 \text{ cm};\ b/a = 2\cdot 51.$$

$$L_e = 2\cdot 303 \times 0\cdot 400 = 0\cdot 922.$$

$$C_e = \frac{1}{2\log_e b/a}\cdot\frac{\sigma}{0\cdot 9}\mu\mu\text{F/cm} = \frac{13\cdot 70}{2(0\cdot 922)0\cdot 9} = 2\cdot 23\ \mu\mu\text{F/cm}.$$

$$C_r = 22\cdot 3\ \mu\mu\text{F/cm}.$$

$$p = 0\cdot 0885\frac{\sigma\rho}{c(\mu\mu\text{F})} = 0\cdot 0885\frac{3\cdot 7\times 525}{22\cdot 3} = 7\cdot 75 \text{ thermal ohms/cm.}$$

$$\Delta\theta = 7\cdot 75\ \text{W}.$$

$$V = 200\ 000.$$

$$S_a = \frac{200\ 000}{1\cdot 176\times 0\cdot 922} = 185\ \text{kV/cm}.$$

$$S_b = \frac{200\ 000}{2\cdot 95\times 0\cdot 922} = 73\cdot 7\ \text{kV/cm}.$$

$$\log_{10}\frac{b}{a} = 0\cdot 400;\quad \frac{1}{10}\log_{10}\frac{b}{a} = 0\cdot 0400.$$

$$\Delta W = (\Delta V)^2\omega C\delta = 20\ 000^2\times 314\frac{22\cdot 3}{10^{12}}\delta = 2\cdot 8\delta.$$

$$AL = \frac{r_2}{r_1} = \frac{S_1}{S_2} = 1\cdot 096.$$

$$I = 200 \text{ amperes.}\quad I^2R = 200^2\frac{0\cdot 620}{10^6} = 0\cdot 0248 \text{ watt/cm.}$$

Sect.	θ	S	δ	$\Delta W = 2\cdot 8\delta$	ΣW	$\Delta\theta = 7\cdot 75$ W
	°C.	kV/cm				
1	65	185	0·0260	0·0726	0·0974	0·75
2	64·25	169	0·0218	0·0610	0·1584	1·23
3	63·02	154	0·0181	0·0507	0·2091	1·62
4	61·40	140	0·0148	0·0415	0·2506	1·94
5	59·46	128	0·0119	0·0332	0·2838	2·20
6	57·26	117	0·0098	0·0274	0·3112	2·41
7	54·85	106	0·0073	0·0204	0·3316	2·56
8	52·29	97	0·0063	0·0176	0·3492	2·70
9	49·59	89	0·0055	0·0154	0·3646	2·82
10	46·77	81	0·0051	0·0143	0·3789	2·93
	43·84	74				

APPENDIX 2.

Relation of Stress D.L.A. to Observed Mass D.L.A.

An approximate method, which is very simple in application, of deducing the stress-D.L.A. characteristic can be obtained as follows:—

In a cable under voltage the total energy generated in the dielectric is given by

$$W = V^2\frac{\sigma\omega}{2\log_e(b/a)}\delta_c \qquad (1)$$

where σ is the permittivity, b and a are the outer and inner radii of the dielectric, and δ_c is the mass D.L.A.

For an elemental ring in the dielectric

$$dW = (Sdr)^2\sigma\omega\frac{r}{2dr}\delta \qquad (2)$$

where S is the electric stress.

For a measurement at a given voltage V we can use the relations:—

$$r = \frac{V}{S\log_e(b/a)} \qquad (3)$$

and

$$\frac{dr}{r} = -\frac{ds}{S} \qquad (4)$$

and put (2) in the form

$$dW = \frac{V^2\sigma\omega}{2\log_e^2(b/a)}\delta\left(-\frac{dS}{S}\right) \qquad (5)$$

Integrating between S_b and S_a and equating to (1), we obtain

$$\delta_c = \frac{1}{\log_e(b/a)}\int_{S_b}^{S_a}\frac{\delta}{S}dS \qquad (6)$$

If now we can use the approximation that over the range of stress covered by any one particular voltage, the D.L.A. is a linear function of the stress, we can substitute the relation

$$\delta = \delta_0 + kS \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in (6), and after integrating we obtain

$$\delta_c = \frac{\delta_a - \delta_b}{\log_e (b/a)} + \delta_0 \quad . \quad . \quad . \quad . \quad . \quad (8)$$

giving the mass D.L.A. in terms of the two terminal stress-D.L.A.'s. The stress $S_{\delta c}$ corresponding to the observed δ_c is given by

$$S_{\delta c} = S_b \frac{(b/a - 1)}{\log_e (b/a)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

That is to say, the D.L.A., δ_c, observed on the cable can be referred to a stress calculated from (9), and in this way the stress-D.L.A. curve can be plotted from the mass-D.L.A. curve.

Equation (9) can be more conveniently arranged in the form

$$S_{\delta c} = V\left\{\frac{1}{\log_e^2 (b/a)}\left(\frac{1}{a} - \frac{1}{b}\right)\right\} \quad . \quad . \quad . \quad (10)$$

The quantity between the braces { } is thus a factor constant for any particular size of cable. Any observed cable D.L.A., δ_c, can then be plotted against a stress obtained by multiplying by this factor the voltage at which δ_c was measured. It is of interest that this stress $S_{\delta c}$ actually occurs in the cable at a radius $r_{\delta c}$ given by

$$\frac{1}{r_{\delta c}} = \frac{1}{\log_e (b/a)}\left(\frac{1}{a} - \frac{1}{b}\right) \quad . \quad . \quad . \quad (11)$$

A graphical method not involving the approximation of linear D.L.A. over the stress range of any one measurement can be obtained as follows:—

Equation (6) can be put in the form*

$$\delta_c = \frac{1}{\log_e (b/a)}\int_{\log S_b}^{\log S_a} \delta \, d(\log_e S) \quad . \quad . \quad . \quad (12)$$

* This equation was first proposed by Mr. M. Stienon. It can be utilized in a number of ways, but the one described which appears to be the most convenient was first proposed by Dr. A. T. Starr. The author is indebted to his colleagues for permission to publish these results here.

Let us assume some function of S such that

$$\int \delta d\,(\log_e S) \equiv f(S) \quad . \quad . \quad . \quad . \quad (13)$$

Then from (12)

$$\delta_c = \frac{1}{\log_e (b/a)}\left[f(S_a) - f(S_c)\right] \quad . \quad . \quad . \quad (14)$$

and from (13)

$$\delta = \frac{d}{d(\log_e S)} f(S) \quad . \quad . \quad . \quad . \quad (15)$$

Equation (14) can be used to determine graphically the shape of the curve $f(S)$ against S. It is to be observed that the shape only is required, and not the absolute level of the curve, since in equation (15) we only require a differential of the $f(S)$ curve.

From equation (14) we see that the quantity $\delta_c \log_e (b/a)$ gives the increase in ordinates of the $f(S)$ curve in going from stress S_b to S_a, both corresponding to the voltage at which the particular value of δ_c was measured. Starting with the lowest voltage at which measurements have been made, we calculate S_b and assume $f(S)$ at this stress to be zero. The quantity $\delta_c \log_e (b/a)$ then gives the value of $f(S)$ at S_a. We can provisionally join these two points by a straight line. Now take a slightly higher voltage corresponding to S_a' and S_b'. The quantity $d_c' \log_e (b/a)$ can be added to the value of the provisional straight line at S_b' to give the value at S_a'.

It may be found that the new point at S_a' requires the provisional straight line to be slightly modified, which in turn will result in a slight alteration of the point at S_a'; but by a short trial-and-error process the three points can be brought into harmony. The curve can thus be extended point by point until the whole stress range has been covered. The curve of $f(S)$ is then replotted against $\log_e S$ instead of S. Tangents to this curve are drawn at a suitably selected number of points and the values of these slopes are taken as values of the differential

$$\frac{d}{d\,(\log_e S)} f(S)$$

and plotted as a curve of δ against S.

[The discussion on this paper will be found on page 116.]

Discussion before the Transmission Section, 20th February, 1935, on the Papers by Dr. Robinson (see page 90) and Dr. Brazier (see page 104).

Dr. E. H. Rayner: The information contained in the two papers emphasizes the importance, for high-voltage cables, of the conditions of cable laying and the avoidance of even a few yards of bad thermal conditions as regards the cooling effect.

With regard to Dr. Robinson's paper, those responsible for the design and proving of cables must have found this magenta test the thing for which they have been looking for many years. An ordinary cable is most intractable from the point of view of research and measurement; it is sealed up, and one cannot see what is happening inside it. To have some method by which the history automatically writes itself must be of very great help to the industry.

The subject of dielectric thermal instability is one which I came to work at many years ago. In the early days of the National Physical Laboratory, the Engineering Standards Committee (now the British Standards Institution) wished for information on the electric strength of insulating materials, and it fell to me to carry out a good deal of this work. In the course of the investigation I had to do a considerable amount of work on the voltage characteristics of insulating materials. I soon came to the conclusion that it was very unprofitable to work blindly without really knowing what was happening, and I therefore set about making an electrostatic wattmeter for the direct measurement of the power wasted in the insulation.

A fortnight ago Mr. Burch described to the Wireless Section the thrill of excitement which he experienced as he watched the deflection of a galvanometer gradually falling to zero, showing him that after many months of work his "oil vapour" pump was at last a success.* I had moments of similar excitement when I was able to watch the process of thermal instability by the rate of change of deflection of my instrument, and in some cases was able to predict to a few seconds the time of breakdown when the voltage had been applied perhaps for an hour. In other cases one could say that failure would not occur, or that it would occur if one very slightly altered the voltage or the frequency. As is stated in Dr. Brazier's paper, one can go almost up to the breakdown point with many of these types of thermal instability without causing any alteration of the dielectric. The delicacy of the balance between stability and instability which leads to destruction is illustrated in the slides which I now propose to show. [Dr. Rayner here exhibited some lantern slides representing some of the results described in his paper on "High-voltage Tests and Energy Losses in Insulating Materials."†]

The measurement of dielectric losses has been the key to high-voltage engineering, making possible the practical developments rendered desirable by economic considerations. The papers indicate not only that measurement is essential to obtain quality, but also that operating voltages have now reached a value when dielectric thermal stability is a quality governing the loading capabilities of cable transmission. Dr. Brazier mentions the limitations which must be overcome, and he suggests the use of materials with a lower rate of increase of loss with rising temperature: one would like to know something about the methods by which that lower rate can be obtained. He does not mention the type of insulation used, but Dr. Robinson states that 23 per cent of resin in a paraffin type of oil was used in his case. I should be interested to know how far that resin compound is responsible for the particular loss curve that Dr. Brazier has been using, and whether the absence of resin would have a material effect on it. The knowledge which has become available in the last few years seems to indicate that the oxygen parts of molecules are very likely associated with dielectric losses, and by doing without the resin, which I imagine contains a good deal of oxygen, one may secure a lower dielectric loss, which with cables of very high voltage is important. That may account for the results obtained with oil-filled cable.

Another interesting point is the statement in Dr. Brazier's paper that, under certain conditions, increasing the dielectric wall in a cable is not much of a safeguard from the point of view of breakdown. There is an analogy there with the strength of a thick tube. Thickening a tube unduly does not add much to the strength, unless one puts it in initial tension. In a similar connection, Lord Kelvin pointed out that the application of a heat-insulating covering to a pipe to keep the heat in might have an exactly opposite effect and keep it cooler; he added that if a man were very thin he would have to wear no clothes in order to keep himself warm.

I think that all the work described in the papers has been done on a Schering bridge in which a vibration galvanometer is used, and the results are obtained in terms of the energy loss associated with the fundamental of the frequency. I should be interested to know whether that method accounts for all the heat generated in the dielectric. Is there any appreciable quantity of heat associated with other frequencies? In other words, does the single-frequency bridge method under these conditions of partial ionization give the same result as a wattmeter method? I quite realize that there is not a wattmeter in existence capable of being worked at 100 to 300 kV which has this great accuracy at almost zero power factor.

Mr. T. R. Scott: With regard to Dr. Robinson's paper, I am disappointed that the author does not develop his arguments in greater detail or, at least, with more supporting data in the first place. He advances the general proposition that, for conservatively-loaded 66-kV cables and cables for all lower voltages (interpolating some of the results from the first paper), breakdown cannot occur unless the coring and tracking mechanism is set up in the region of maximum stress. It is suggested, therefore, that the way to improve quality of cable is to concentrate on the elevation of the voltage/time-to-breakdown (V.T.B.) characteristic. This method of improving and maintaining quality is a favourite one in certain countries, and has given reasonably satisfactory results. One may question, however, whether it is the

* C. R. Burch and C. Sykes: "Continuously Evacuated Valves and their Associated Equipment," *Journal I.E.E.*, 1935, vol. 77, p. 129.

† *Journal I.E.E.*, 1912, vol. 49, p. 3

best method of procedure for improving the quality of the cable, and I should like to make that point in two different ways.

The usual objection raised to accepting a standard V.T.B. characteristic on a virgin cable as a basis is that, when the cable goes into service, it is apt to suffer some kind of change, which will mean that the results obtained on the test floors are of very little use later. To meet that objection, the usual suggestion is some form of stability life test or accelerated ageing. Under such a type of test, cables usually fall into one of three categories. There is one class of cable which tends straight away towards breakdown—in a reasonably long period, perhaps, but still towards breakdown. That class of cable requires no comment. The second class shows instability at some period of its career, and then settles down to a life where its characteristics are not the same as on the test floor originally, but where its new characteristics are invariant over very long periods of time. It such a cable is removed and re-tested on the test floor, it will be found that the V.T.B. characteristic has deteriorated, but the characteristic is still eminently satisfactory from a practical point of view. In the case of the third and rarest class of cable, the V.T.B. characteristic does not appear to change to any appreciable extent.

The question which arises, therefore, is whether it is better to concentrate on getting a high V.T.B. characteristic or on getting a cable in which the V.T.B. characteristic is maintained throughout its service life. Dr. Robinson is not very clear in the definition of his views on the matter, apart from the indication that he would like, by using, say, paper of high air-resistivity with low porosity, to obtain an initially high V.T.B. characteristic. Such procedure may militate against obtaining the invariant requirement.

The problem can be presented in another way, which perhaps brings it more into the sphere of practical politics. A single-core cable and a 3-core H-type cable were made up simultaneously some time ago with exactly the same materials, construction, and design, and were processed in the same plant under exactly similar conditions. The results obtained on the test floor were similar. Everything about the two types of cable was apparently identical. When the cables went into service the single-core type immediately began to exhibit breakdown characteristics, and had a service life of from 4 weeks at 25 per cent over-voltage to 6 months at working voltage. The 3-core cable survived 3 years' service life; it was then returned to the factory and electrically showed no indications of having been in service. There is nothing in Dr. Robinson's paper to suggest why the single-core cable should be more liable to breakdown than the 3-core cable, except that cavitation may have had some effect, since it is generally assumed nowadays that 3-core H-type cable has superior qualities with regard to the avoidance of cavitation. It is rather incredible that the elimination or minimization of cavitation will produce so marked a result, but I am curious to know what other factor could be operating which resulted in the 3-core cable maintaining its characteristics while the single-core cable did not. Subsequent experience shows that single-core cables can be made to give similar results if an attempt is made to reproduce conditions similar to those existing in the 3-core insulation. The experience indicates that a very good case can be made out for designing cables in such a way that they will retain their original characteristics, rather than attempting to build up an exceedingly high characteristic which may degenerate in service. The ideal, of course, is to obtain a high and constant characteristic in operation.

With regard to thermal instability, there is one point on which the papers give no information. Going back to the time of Evershed and his fundamental paper,* moisture has always been considered to be a fruitful source of thermal-instability phenomena, and, since moisture faults are not altogether unknown in the cable world, it would be interesting to have Dr. Brazier's views on how moisture can intervene in a cable so as to give thermal instability. Is moisture breakdown altogether of the thermal-instability characteristic type, or does Dr. Robinson's tracking mechanism intervene at all? I find it difficult to apply the latter principle to the breakdown of cables of 10 kV and lower voltages (many of which are associated with moisture effects), unless thermal phenomena are also present.

Mr. J. K. Webb: I am particularly interested in the effect of the application of gas pressure to a cable, as mentioned in paragraph A, Section (6), of Dr. Robinson's paper. What are the disadvantages of this process, apart from the unreliability of lead sheathing? At what voltage does tracking occur in a gas-pressure cable, and what voltage induces wax formation?

Referring to paragraph H of the same Section, is the implication here that solid-type cables cannot be impregnated to the same degree as oil-filled cables? Can the magnitude of these high-frequency components be taken as a criterion of cable quality?

I should like to join with Dr. Rayner in asking a question regarding the use of resin, for which the authors show a predilection. Hirshfield, Meyer, and Connell, in the report referred to in the Bibliography to Dr. Robinson's paper, suggest that " any beneficial action which it may exert is probably due to its property of becoming an increasingly better conductor with increasing temperature. It therefore appears that its beneficial effect is in causing a much greater portion of the current to flow around the bad spots in the dielectric instead of flowing through them." Dr. Brazier's first slide, giving the relation between the dielectric loss angle (D.L.A.) and the temperature of the compound, showed a steep rise of power factor or D.L.A. with temperature; this is a peculiarity of resin mixtures, and it can be avoided by the use of a mineral oil. This would appear to have an important bearing on the values of thermal stability as calculated by him, if " bad spots " could be otherwise suppressed. It is noteworthy that for some time past in America the tendency has been away from resin, but we in this country, with one notable exception, appear to be more conservative. Can the authors give any good justification for the use of resin?

With regard to the question of the waxing of cables, are we now to regard this as inevitable? Mains engineers view wax with suspicion, since they consider that it

* "The Characteristics of Insulation Resistance," *Journal I.E.E.*, 1914, vol. 52, p. 51.

indicates deterioration; yet, as is stated in Dr. Robinson's paper (page 91), and as has also been stated by Hirshfield, Meyer, and Connell, cables which are so heavily waxed that no free oil remains have been known to work satisfactorily for years. Should we not rather look upon waxing as a kind of seasoning process, and seek to control it? After all, wax itself is an excellent dielectric, and much more stable than the original compound. The only difficulty we are up against is the formation of gaseous by-products during condensation, and I should like to ask the authors whether they can give us any information concerning the magnitude and effect of these products. The initial formation of wax results in a power factor or D.L.A. which alters in proportion to the waxing, and it may be necessary to take this into consideration in the analysis of thermal instability given in Dr. Brazier's paper. This paper, however, seems to me to be rather looking ahead; failure in service resulting from thermal instability is not our immediate concern at present-day voltages, but I agree that it is a factor worth bearing in mind, especially when voltages of the order of 220 kV are contemplated.

Finally, can the authors give us any information concerning the rate at which waxing takes place in relation to frequency? I myself have found that, while there is a big increase between 50 and 10 000 cycles per sec., there is not nearly so much between 10 000 and 200 000 cycles per sec.

Mr. F. W. Main: Paragraph A, Section (6), of Dr. Robinson's paper refers to the character of the deterioration found in the dielectric of a cable-end under voltage test when gas is applied to the terminal. Reference is being made here, no doubt, to the practice adopted to overcome the flash-over of cable-ends during high-voltage tests. In such a method the end terminates in a sealing bell, which is filled with a gas such as nitrogen to a pressure in the neighbourhood of 200 lb. per sq. in. The resulting brilliant tree formation is shown in Fig. 5. It would appear from this illustration that either the dielectric as a whole contains air spaces or spaces of low pressure, or, owing to disturbance in handling, air has become entrapped between the papers at the ends, and, although the whole end is in the presence of gas under pressure, there is clear evidence of ionization with treeing.

Later in the same paragraph Dr. Robinson uses the expression "pressure cable" in relation to specimen H in Fig. 5. The original pressure cable is that type of cable, manufactured and supplied in Great Britain and on the Continent, in which the dielectric is under mechanical pressure. The pressure medium is usually gas, such as nitrogen, which is not in actual contact with the dielectric but acts through an impermeable diaphragm such as a thin lead sheath. In such a cable, as normally constructed, ionization treeing as depicted in Fig. 5 is impossible: it is contrary to the theory of the pressure cable and has never been observed in practice by manufacturers of this particular cable in this country or abroad. I therefore think that Dr. Robinson is still referring here to a cable-end filled with gas under pressure, and not to a pressure cable. I should be glad of his confirmation of this.

Dr. Robinson cites the oil-filled cable as an example of the phenomena described in paragraph J, page 95; I should like to mention the pressure cable as a further example.

Fig. 3 of Dr. Brazier's paper shows a family of typical super-tension cable curves which are used in the calculations outlined in the paper, and therefore influence the results obtained by the method. Similar curves obtained from a pressure cable would, I submit, form a less unruly family than this.

I am in sympathy with Dr. Brazier's note on page 104 regarding the term "power factor." I prefer to use the term "power factor of the dielectric" rather than "power factor of the cable" when referring to the cosine of the angle ϕ between the admittance vector and the resistance vector; and, of course, $\delta = \frac{1}{2}\pi - \phi$.

(*Communicated*): With regard to Figs. 10 and 11 of Dr. Robinson's paper, which depict developed sections of the dielectric, at the meeting it was suggested by Mr. Borlase Matthews that more effective barrier action might be obtained by bevelling the edges of the paper tapes. Lengths of cable were manufactured on these lines 7 or 8 years ago to Patent No. 261724, both in this country and on the Continent. The paper was chamfered along both edges of the strips. Although a slight improvement was observed, the results did not justify the expense and trouble of the modification.

It is indicated in Dr. Brazier's paper that the curves shown in Fig. 3 are not representative of the best modern cable practice, and I would point out that results obtained from calculations based upon such poor curves would tend to lead to adverse conclusions respecting thermal instability, and thereby give a wrong conception of present-day quality. The characteristic curves obtained on a virgin cable of modern manufacture, no matter what the type, would be far superior to those depicted. Further, for a type such as the pressure cable, specially designed to eliminate low-pressure spaces in the dielectric at all prevailing temperatures, there would be practically no departure from the initial curves after the cable had been subjected to an indefinite number of heat cycles up to 80°, 90°, or even 100° C., under electric stress.

Dr. A. T. Starr: Dealing with Dr. Robinson's paper, the effect of direct-current stress is particularly interesting. It would seem that the basis of the author's explanation implies the same sort of phenomenon as Gemant suggested, namely, that when we apply an electrical stress to a void, as the stress increases there comes a point when the void flashes over, the positive charge going in the direction of the stress and the negative in the other direction. Thus a stress opposite to that applied is produced in the void, and then the void behaves in the normal way until the stress increases further. The reference to Brown and Sporing (page 102) I find slightly misleading. In their case the d.c. stress caused no energy loss, but they were concerned only with voids completely isolated in the dielectric, whereas the voids which are responsible for the tracking mechanism described in Dr. Robinson's paper are more or less connected to the conductor by the conducting track.

My discussion of Dr. Brazier's paper is concerned

with a number of isolated points. On page 108 the author states a very important theorem of extreme use, and says that "the step-by-step method of integration can be applied to non-circular cables of any shape." This is perfectly true, but the proof as given is inadequate. C_r, P_r, here have no meaning. They refer, I suppose, to the capacitance and the thermal resistance between concentric rings in a circular cable; in a non-circular cable, however, there will not be any concentric rings. The theorem can be proved adequately in the following way. It can be shown by two methods, the neater method being due to Mr. Stienon, that when the D.L.A. is independent of the stress the equipotentials and isothermals in the dielectric coincide. We can therefore divide the dielectric into a number of rings by means of the conductor sheath and equipotentials, and then in the case of the non-circular cable the work goes on exactly as for the circular cable. It is very difficult to apply this step-by-step method to a non-circular cable whose D.L.A. depends on the stress, but the following procedure may give reasonable results. The electrostatic problem is first solved, and then the equipotentials and the lines of equal stress are drawn. Imagine the dielectric divided into ten rings bounded by equipotentials: each ring has areas under different stresses. The dielectric loss in each ring is obtained by addition, and then the rings are dealt with as before.

On page 111 of Dr. Brazier's paper it is stated: "In practice, what is required is to know the thermal state at a given conductor temperature, and what conductor current can be carried in this state." I suggest that the conductor temperature is quite irrelevant, provided it is not so high as to char the paper. What the mains engineer wants to know is what current his cable will carry under certain conditions of laying, and the designer wants to know the same thing, but for general conditions of laying. The types of instability curves shown in Fig. 7 are most suitable for the designer, because he has to draw only one straight line for a given pair of values of external thermal resistance and ambient temperature. It suffers from a slight disadvantage in that the straight line will meet the important curves at a small angle, and the error is thus increased. It is much better for the cable user to have a diagram of rather a different type. Given an external thermal resistance and an ambient temperature, we assume any value of sheath temperature, and we know immediately by simple division what sheath watts can be dissipated. We then proceed by the step-by-step method from the sheath to the conductor, and find how much conductor dissipation is allowable.

If we plot current against sheath temperature, we get a curve like an inverted parabola, and the maximum is clearly discernible. For example, let us consider an experimental cable, 3-core, 132-kV, 0·3-sq. in., 0·6-in. wall, to work at an over-voltage of 50 per cent. The internal thermal resistance per core was calculated to be 118 thermal ohms, the external resistance was taken as 140 thermal ohms, and the ambient temperature as 15° C. Fig. A gives the sheath and copper temperatures and the current.

It is also possible, when calculating in this way, to get an approximate curve for a different ambient temperature without going through the step-by-step method all over again. If the ambient temperature increases by 5 deg. C., we merely take a corresponding increase in sheath temperature. The sheath watts are therefore the same, and we take two of the values of dielectric loss from the preceding calculations, so that the conductor watts are greater than one calculated value and less than another. Quite a good approximation is obtained in this way. The most suitable curves for a cable user, therefore, are a series of curves very much like parabolas for different external thermal resistances and for one ambient temperature. For the cable designer, however, such curves are not of much use, and a more accurate

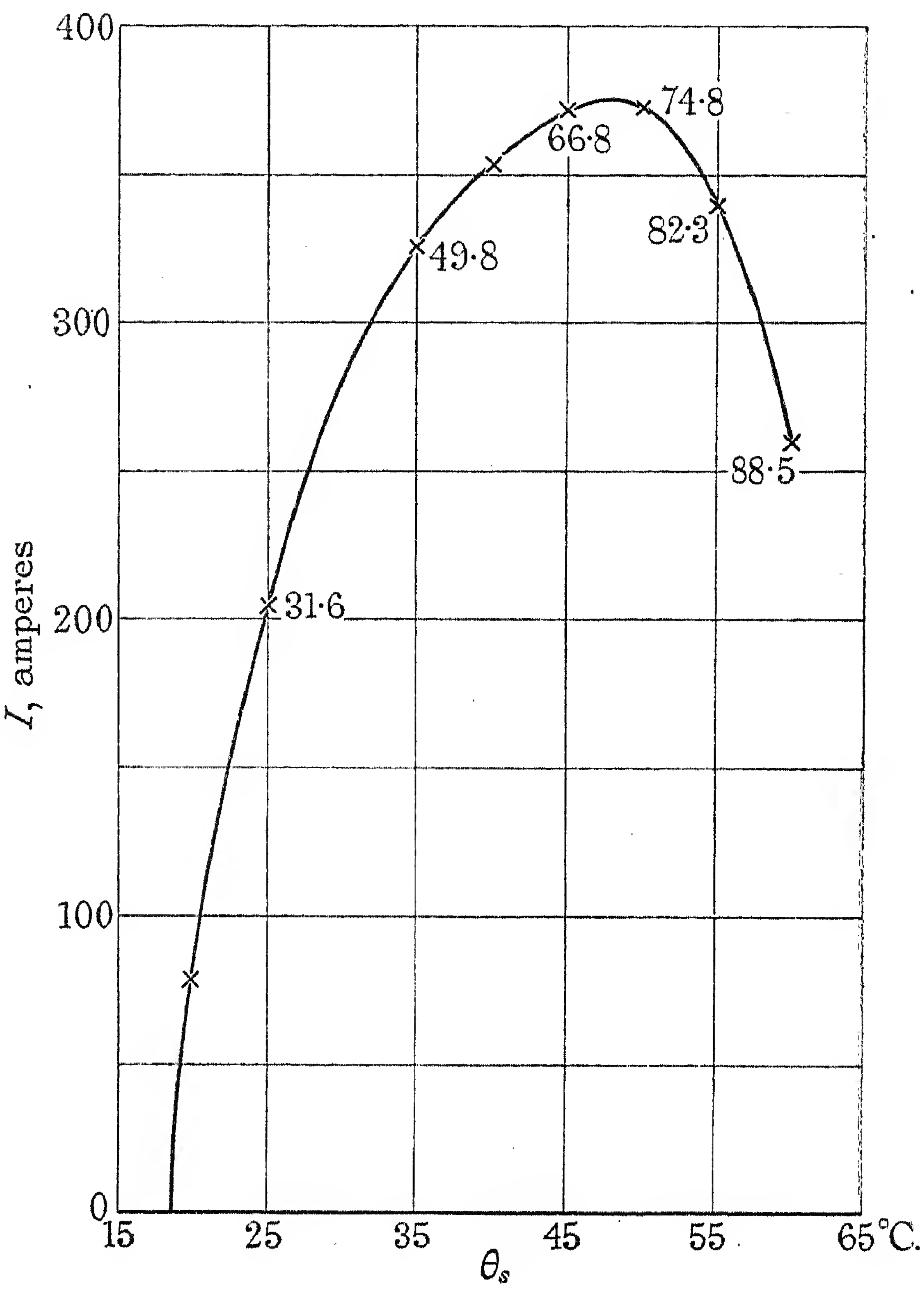


FIG. A.

The numbers on the curve indicate conductor temperatures in deg. C. θ_s = sheath temperature.

set of curves is obtained in the following way. First, dielectric losses are plotted against sheath watts for given values of sheath temperature. Then for a given external resistance the sheath watts are calculated from the simple formula connecting the sheath and ambient temperatures and the external thermal resistance. The corresponding dielectric loss is read off from the curve, and subtraction gives the conductor watts. The cable user's diagram can then be drawn.

I should like to describe two methods of finding stress D.L.A. from mass D.L.A. which do not suffer from a slight arbitrariness which occurs in the method employed by Dr. Brazier. In the first case we assume a polynomial expression for the mass-D.L.A. curve and the stress-D.L.A. curve. The former is found by measure-

ment, and a polynomial fitted. The application of equation (6) in the first paper then yields the coefficients for the polynomial representing the stress-D.L.A. curve, which can then be plotted. There is, however, another method which is rather more useful. By means of equation (14) in Dr. Brazier's paper we correlate the D.L.A. at a certain stress with the D.L.A. at a very much lower stress plus a certain simple quantity which can be calculated from the mass-D.L.A. curve. We attach to this lower stress any kind of D.L.A. we like, preferably a constant value, and then find that we can calculate the D.L.A. curve for stress very simply from the D.L.A. curve for the cable.

Mr. R. C. Mildner: I propose to confine my remarks to Dr. Robinson's paper. One Continental cable maker has suggested the use of polystyrene tapes in the manufacture of his cable, and I should like to ask the author what would be the effect of applying next to the conductor of, say, a 66-kV cable a thin layer of dielectric the long-time breakdown strength of which is considerably higher than the maximum working stress. Is it the author's opinion that such a cable might be expected to survive failure indefinitely? According to his mechanism, coring cannot take place in such a dielectric, and consequently the interior of the dielectric might be deteriorated and still survive breakdown.

It cannot be too strongly emphasized that this type of failure is only the final stage of a deterioration which progresses continuously throughout the active life of the dielectric.

Dealing with short-time breakdown tests of the order of several hours, if a cable dielectric is subjected to stress for a period corresponding, say, to 75 per cent of its normal life, it will be found to have suffered no ill effects which can be detected by physical tests, other than an impaired ability to withstand subsequent stressing. What is the nature of this deterioration which enables a dielectric to "know" that it has been subjected to excessive stressing? I should like to suggest that it is the gradual absorption by the dielectric of gas liberated by the ionic bombardment, and that the initiation of the coring and tracking mechanism coincides with some phase of this gas absorption. Similarly, with high-voltage cable tested at moderate over-voltages of the order of 50 per cent, we have observed that some 66-kV cables, having initially a short-time breakdown strength of considerably over 300 kV, deteriorated in the course of several months' testing until their short-time breakdown strength was of the order of 145 kV, without trouble occurring at the test voltage. It seems to me that this observation gives promise of a useful criterion in any accelerated-ageing test for super-tension cables working at moderate over-voltages and subjected to heat cycles.

Mr. W. Bibby: Dr. Robinson's paper indicates that one of the main causes of treeing is the presence of voids, and I should like the author's opinion on whether it is possible to eliminate voids in either the external pressure type of cable or the internal pressure type. Regarding the d.c. testing of cables, I should like to know whether a d.c. failure at a weak place may cause breakdown at some other place which, although weak, would still sustain the a.c. voltage for long periods. The author says something about severe handling; unless the cable is handled carefully there are possibilities of creating voids, e.g. by the insulating tapes being lapped on the cables in the wrong direction.

Dr. Brazier's paper describes methods which are no doubt invaluable where the testing conditions are purposely made bordering on the unstable; supply engineers who may be feeling nervous should look at the table in Appendix 1, which shows that, as would be expected, the ratio of dielectric loss to copper loss is very high—15:1. In practice, of course, this ratio would only be of the order of 10 per cent, so that one would only expect, on a normal 66-kV cable, a difference in temperature between the sheath and copper of the order of 3 deg. C. due to dielectric loss when the cable was working at its maximum conductor temperature. A small variation in external conditions may produce a far greater change in conductor temperature than would be represented by the difference between the results given by the step-by-step method and the approximate method.

Most practical cable engineers, particularly those who 10 or 15 years ago were thinking about 33-kV and 66-kV cable, will be conversant with Fig. 11. The dielectric loss in those days was a factor to be taken into account, even under normal working conditions. The right-hand diagram in Fig. 11 undoubtedly represents an unstable condition for test purposes, but in practice the temperature of that cable would never reach the point where the vertical line is shown; so that, although the cable may be called unstable as regards test conditions, it would certainly be quite stable in practice.

Curves are given in the paper for D.L.A. plotted against voltage and temperature, and naturally the values given in these curves could be correlated with the power factor or D.L.A. in a cable in which there is core heating. It would be useful if some indication could be given of the correlation (if any) which has been obtained in this way.

Dealing with cable design in general, there are several features that one could mention. To refer to one or two, since void formation is a factor both in treeing and in deterioration one naturally concludes that an oil-filled cable, or alternatively one using a thinner oil containing no resin, would be beneficial. Almost all electrical apparatus has attached to it indicating devices to inform one as to its condition, but a cable is put into the ground and forgotten. There is no doubt that it would be beneficial even if only thermocouples were placed in parts of the route where the effect of the proximity of other cables is serious. In London to-day there are spots where in the near future the condition will arise that the addition of further cables will not help the situation. I would point out that cables, unlike electrical machinery, are not provided with cooling apparatus.

Mr. S. A. Stevens: There is one small point which none of the previous speakers has raised, perhaps because thermal instability has not yet become a serious problem with regard to cables. The point is this: how can we define a factor of safety? Referring to Fig. 1 of Dr. Brazier's paper, it is very hard indeed to define just what factor of safety we have if we are working at a point

such as L. I should like to know what the author proposes to do as regards stating a factor of safety and determining suitable safe operating conditions for high-voltage cables. The practice in the firm with which I am associated is to work on a factor of safety represented by a given number of degrees above the normal maximum operating ambient temperature; thus if we are told the normal maximum operating ambient temperature is 35° C. we find a loss curve to which the dissipation curve will be tangential when we have an ambient temperature a given number of degrees above that point. I should be glad to know whether the author has any comments to make on this matter.

Mr. R. Borlase Matthews: Referring to Figs. 10 and 11 in Dr. Robinson's paper, would it not be an advantage, instead of using clean-cut edges to the paper winding strip, to have the edges frayed or tapered so as to make a more homogeneous joint? This suggestion might be carried to the point of having paper-composition sheathing machines instead of strip winding machines. The suggested machines would be on the lines of sheathing machines and would provide a complete paper-composition cover, in several separate layers for the sake of the subsequent flexibility of the cable, thus eliminating the joints of the paper strips.

Looking at the papers from the point of view of the ordinary engineering reader who is not a cable expert, it seems to me that the authors should give an explanation of some of their abbreviations. As an illustration, on page 118 of Dr. Brazier's paper there is a reference to the "D.L.A./temperature characteristic"; an expression such as this deserves a footnote.

Referring to Fig. 2 of the same paper, it seems to me to be very fortunate for the cable makers that the higher-voltage cables are of the single-core cylindrical type, because, owing to the increased area of the dielectric as it gets farther away from the core, there is an increased surface for dissipating the heat. In such cables, if it were not for that fact, it would seem to be rather important to measure the quantity of heat, whereas for present purposes the temperature gradient would seem to be quite sufficient.

Mr. W. A. Del Mar (U.S.A.) (*communicated*): Dr. Robinson correctly quotes me as having stated that tree patterns occur in the interior of a cable, unaccompanied by charring of the papers above and below. Fortunately, I have kept some of the examples upon which I based this statement, and have been able to follow Dr. Robinson's suggestion to examine the apparently uninjured papers with a microscope. There are no perforations but there are microscopic carbonized spots, which are located with reference to the trees as Dr. Robinson's theory would require.

The first evidences of carbonization are in the second layer of paper from the conductor and are situated directly over the channels between the edges of the first paper. This suggests that the disturbances which caused the carbonization originated in the oil between tape edges, and it would therefore seem important to keep down the electric stress in that oil by making the permittivity of the paper as little as possible in excess of that of the oil. It was noted that the "corings" always originate where the apex of a strand crosses an inter-edge channel, i.e. where the electric stress in the oil is greatest.

I am thus able to confirm Dr. Robinson's theory that the tree type of failure starts with the formation of a carbon needle based on the conductor surface and stretching radially outward. The origin of the conducting needles, however, remains to be explained, and perhaps the following theory propounded by Dr. Harold S. Osborne* may furnish the clue.

"Let us accept the assumption that an excessive potential gradient at any point always disrupts the dielectric at that point. It seems evident upon consideration that, even in a perfectly homogeneous dielectric, the uniform breakdown required by the Russell hypothesis would be a condition of unstable equilibrium, for if the breakdown proceeds a little farther at one point than at the points around it, the charge flowing into that advanced point will reduce the stress on the surrounding points, and the more intense field at the end of the advanced point will tend to push the breakdown farther and farther into the dielectric. Commercial dielectrics, which cannot be perfectly homogeneous, should then be certainly expected to break down not uniformly, but at a number of points, so that the incipient breakdown produces much the same effect as a number of needlepoints thrust into the insulation."

Mr. J. S. Hastie (*communicated*): Dr. Robinson differentiates between "coring" and "tracking," the former being the carbonization through a paper as a result of a puncture and the latter the tree formation on the surface of a paper. When conducting a large number of breakdown tests some little time ago we found that the tree formation itself could be split into two different classes. In the first class the tree formation was on the surface of the papers and could be easily removed by scraping lightly with a penknife or the finger nail; in the second class the trunk of the tree and some of the main branches had burnt deeply into, and in some cases right through, the papers. These observations were made at the time when experiments were being carried out with a view to establishing a method of determining the residual moisture content of samples of cable dielectric. It was observed that, when the residual moisture content was fairly high, the burning of the papers was very pronounced, but when the residual moisture content was low, i.e. below 0·075 per cent, the tree formation, although prolific, was confined almost entirely to the surface of the papers. It would be interesting to know whether Dr. Robinson has observed this effect. It may be, however, that all the cables he examined had very low residual moisture contents.

He states most emphatically several times in his paper that, although the maximum apparent deterioration occurs at a distance from the conductor, there is no evidence that such deterioration has any influence on the eventual breakdown of a cable. While this may be so in the case of a length of virgin cable, it is rather difficult to accept such a statement for the case of cables that have been subjected to severe heat cycles. When a cable is subjected to repeated heat cycles, the compound gradually migrates to the outside of the dielectric

* *Transactions of the American I.E.E.*, 1910, vol. 29, p. 1574.

and a break takes place in the compound column on cooling.

On examination of certain solid-type cables after repeated heat cycles to fairly high temperatures it is generally found that a belt of papers exists towards the middle of the dielectric which is seriously lacking in compound. The papers themselves are dry and have a matt surface, the gap between convolutions being quite devoid of compound. This belt of 15 to 25 dry papers is generally located at a distance of approximately one-third to one-half of the thickness of the dielectric from the conductor, depending on the geometry of the sample. The papers on both sides of this belt, that is towards the conductor and towards the screen, are generally found to be in excellent condition, being well impregnated and all gaps between convolutions absolutely full of compound.

On subjecting a cable in this condition to high electric stresses, severe burning was found to have taken place in this belt of dry papers, and absolutely no connection could be found between this burning and either of the electrodes. Possibly Dr. Robinson has some further evidence which has been overlooked in the case referred to above.

Some rather peculiar test results obtained on another length of cable in the condition described above may be of interest. The cable had a 0·3-sq. in. oval conductor and was insulated for 33 kV. After repeated heat cycles to fairly high temperatures the power factors at working voltage and twice working voltage when corrected to 15° C. were found to be 0·39 per cent and 0·54 per cent respectively, thus indicating severe ionization. On examination of samples of the cable it was found to be exactly as described above, i.e. there was a belt of dry papers approximately one-third of the thickness of the insulation from the conductor. Further heat cycles with and without applied voltage did not seem to make any alteration to the value of the power factor, neither did prolonged resting without voltage nor prolonged periods under working voltage. When 150 per cent working voltage was applied for some time a very slight improvement in the power factor was found. The voltage was then increased to twice working voltage, and the power factor was now found to improve rapidly. After approximately 200 to 250 hours under twice working voltage the power factor had recovered to the figure obtained on the cable immediately after completion of manufacture, i.e. 0·36 per cent at working voltage and twice working voltage. On examination of short pieces cut from the cable it was found that the compound had somehow returned to the dry places and the cable throughout had the appearance of a freshly impregnated length. Part of the cable after this recovery was subjected to twice working voltage for over 1 000 hours, and no alteration in the power factor took place. It would be interesting to know whether Dr. Robinson has come across such a case as this, and whether he can give any explanation. It may be that, under the effect of the electrical stress, the compound moved towards the region of lower permittivity; or, again, gas in the voids may have been forced into solution, thus reducing the pressure and facilitating the return of the compound.

It would almost appear as if the cable described above would give much more satisfactory service when operated at a high electric stress rather than at the comparatively low stress for which it was designed. It would appear also as if stability tests conducted with some fairly high and perhaps critical value of applied voltage would show a much better performance than stability tests conducted with working voltage or with no voltage at all; but it has unfortunately been impossible so far to conduct the experiments necessary either to prove or to disprove this.

With reference to Figs. 8 and 9 in Dr. Robinson's paper, it is unfortunate that the tests were carried out on papers of varying thickness and varying density, as it is well known that thin samples of most solid materials give a higher electric strength in volts per unit thickness than thicker samples of the same material. This fact is made use of by the designers of power condensers, who frequently use a large number of thin papers in preference to a small number of thick papers so as to give a higher total breakdown strength. It is interesting, however, to see that a considerable improvement is obtained by the use of 3·5-mil paper instead of the more usual 4·5–5-mil paper.

In Dr. Brazier's paper it is pointed out that the thermal stability of the dielectric is of importance in the case of cables for 66 kV and above. When we were conducting breakdown tests recently, however, on 10-kV oval-conductor screened cables, we observed two entirely different types of failures. The tests were being conducted with a view to producing the time/voltage breakdown curve for the cable and it was found that, almost without exception, the long-time breakdowns at voltages approximating to the asymptotic value took place on the minor axis of the cable and were accompanied by severe tree formation through the dielectric. The short-time breakdowns at high voltage, however, generally took place on the major axis and were in the form of clean punctures, almost no tree formation being visible anywhere in the cable. The cable had previously been subjected to repeated load cycles to fairly high temperatures, and the dielectric was soft on the minor axis although still fairly hard on the major axis. The smell of the samples after breakdown corresponded exactly with the author's description, so that it would appear that the low-voltage long-time failures were of the tracking type in the soft portion of the dielectric on the minor axis while the high-voltage short-time failures were of the thermal type on the major axis, where the electrical stress at the surface of the conductor was greatest. It would be very interesting to know whether the author has observed this effect when testing oval-conductor cables.

Mr. M. Hochstadter (Belgium) (*communicated*): In the first paragraph of Section (6) and in Fig. 5 of his paper, Dr. Robinson describes the influence of pressure on the treeing. The wording of this section is such as to convey the impression that Dr. Robinson's experimental results and conclusions are representative of the influence of mechanical pressure upon cable dielectrics in general, and for pressure cable in particular. I understand, however, that his tests have been carried out on cables the dielectric of which contains gas under pressure. His results and conclusions, therefore, are valid for

such cable only, which should be called "gas-filled cable."

The term "pressure cable" is incorrectly used by Dr. Robinson. A pressure cable contains no gas in its dielectric; on the contrary, its dielectric is separated by an impervious pliable wall from the pressure medium, which may be a gas. The latter compresses the dielectric through the wall. This type of cable is the only one with the dielectric under pressure which has not only been invented but also thoroughly investigated and put to practical use. The claims which have been made for it have been substantiated by the operating results of installations of such cables which have been in service for several years.

The inventors* and manufacturers of this type of cable have given it the name "pressure cable," which name should be reserved for this type of cable, in order to distinguish it from other types, more particularly from "gas-filled" cables.

In none of the breakdown tests on this type of cable which have been made during the past few years on the Continent have treeing, waxing, or carbonization been observed. In every case breakdown has been due to a straight-through puncture, without any signs of deterioration. These tests have extended over periods up to thousands of hours. From this point of view Dr. Robinson's test-results, more particularly those in Fig. 5, show clearly the difference in the electrical behaviour of a gas-filled cable as compared with that of a "pressure cable," and the advantages of the latter type.

My remarks in regard to Dr. Brazier's paper refer particularly to the second paragraph on page 104, to Figs. 3 and 15, and to the second paragraph on page 112, in which latter the author mentions an article by Dr. Vogel and myself.

The author is evidently in error in stating: "Very little attention, however, appears to have been paid to the question of thermal instability in cables." About 6 years ago, in the room in which we are now sitting, I read a paper† giving a rather complete survey on thermal breakdown and on the possibilities of breakdown of cables by thermal instability. Most of the principal points stressed by Dr. Brazier will be found in that paper, but I went even farther than him in that I took into consideration the effect of time and of a certain temperature limit on the thermal breakdown, and thus was able to explain the whole time/voltage characteristic of a cable on thermal grounds.

In a paper‡ published in 1922 I dealt with the influence of the dielectric losses on the rating of cables, and described an experimental investigation of the thermal stability of a particular single-core cable. It was found that this cable would become unstable if tested with double the operating voltage whilst loaded with $1\frac{1}{2}$ times its normal rated current. These conditions are similar to those stressed by the present author, and the cable which I used then, 15 or 16 years ago, gave similar results to those obtained on his cable. Such results are not representative, of course, of our greatly improved present-day cables.

* British Patents 264135, 366673, and others.
† "Testing High-Tension Cable for Reliability in Service," *Electrical Power Engineer*, 1928, vol. 10, pp. 307, 351.
‡ *Elektrotechnische Zeitschrift*, 1922, vol. 43, p. 205.

Curves of the type shown in Figs. 6 and 7 are to be found in a paper* on thermal instability of cables which was published as long ago as 1917.

Dr. Brazier confirms that cables may break down from thermal reasons if their dielectric-loss curve is sufficiently unfavourable in actual value and in slope at high temperatures. He also confirms the fact that thermal instability of a cable is facilitated if the cable is not only under voltage but also under current load. He does not, however, give a convincing answer to the question: Do present-day low-loss cables really fail from thermal reasons when they are subjected to breakdown tests without current load? This question seems to me to be the main issue of this problem, not only theoretically but also practically. The answer to this question once given, the more complicated problem may be solved of how a particular cable behaves under the combined action of voltage and current. The latter problem is only of restricted importance for the design of modern types of cables, e.g. the pressure cable and the oil-filled cable, which can easily withstand a prolonged test at twice the normal operating voltage and full current load. On the other hand, this problem is difficult to solve in a definite manner for the ordinary solid cables, the stability of which also depends on load variations.

I would point out that breakdowns such as those illustrated in Fig. 15 of Dr. Brazier's paper are not due to thermal instability of the cable as a whole. They are due to what have been known for many years as "hot spots" in the ordinary type of solid cable. A hot spot may be described as a thermo-electric breakdown; it is initiated not by thermal instability but by some local deficiency followed by the production of an abnormal amount of heat at this particular spot. To call this a breakdown of the cable arising from thermal instability is not even compatible with the author's definition in the last paragraph of col. 1, page 105.

Dr. Brazier seems to have misinterpreted in some respects the recent paper† by Dr. Vogel and myself. As a matter of fact, the contradiction which he sees between our results and his own does not exist. We did not work with the ordinary solid cables as he has done, because, on account of the complications of the process of thermo-electric breakdown of such cables caused by lack of homogeneity, no dependable solution to our problem could be derived from them. We therefore limited our investigations to a type of cable which is essentially uniform in structure and behaviour, namely the pressure cable. In the particular case which he cites we found that the pressure cable, which had a long-time breakdown value of more than 40 kV per mm, was still very stable with regard to thermal conditions when being stressed at 35 kV per mm. It was possible to heat the lead sheath of this cable from room temperature up to more than 100° C. without disturbing its thermal stability under a stress of 35 kV per mm, a far higher value than those employed by Dr. Brazier. Dr. Vogel and I were perfectly acquainted with the fact that it is possible to get a cable into the zone of thermal instability, either by raising the ambient temperature of the cable or by adding to the dielectric loss another

* A. F. Bang and H. C. Louis: *Transactions of the American I.E.E.*, 1917 vol. 36, p. 431.
† *Elektrotechnik und Maschinenbau*, 1933, vol 51, p. 218.

loss due to heating the conductor with current. In our experiments a definite breakdown due to thermal instability was even intentionally obtained (see Figs. 5 and 6 of our paper) with a method very similar to that applied by the author, namely, by heating of the lead sheath. Thus his contention that our cable would have become thermally unstable if sufficient current load had been added when it was under a stress of 35 kV per mm is not at all contradictory to our paper.

Since the publication of that paper further experiments have been made on pressure cables at stresses exceeding 35 kV per mm; it has been found that, whilst a cable may still be quite stable at 35 kV per mm, it may become thermally unstable under stresses higher than 40 kV per mm without additional heating from other sources. In one particularly simple experiment a 3-conductor cable was subjected to long-time breakdown tests in different ways. It was found that breakdown occurred, say, above 40 kV per mm if only one core was stressed, above 35 kV per mm if two cores were in parallel, and above 30 kV per mm if all three cores were being subjected to voltage stress. No particular hot spots were noticed, and the temperature control showed in each case the rise typical of thermal instability when a temperature of about 110° C. was reached. Examination of the dielectric showed a straight-through burn-out, without other signs of deterioration.

Mr. A. M. Thomas (*communicated*): I note that Dr. Robinson found that the breakdown voltages of samples of cable when tested with alternating current in conjunction with a superimposed direct current were independent of the latter. The superimposed direct current was such that in some cases the conductor was always positive, and in other cases negative, with respect to the sheath. According to Dr. Robinson's theory the breakdown of the cable depends upon ionization in gaseous voids. It is clear that when the superimposed direct current is such that the conductor is always positive, positive ions are repelled towards the sheath, whereas when the conductor is always negative, negative ions alone travel outwards. It is therefore somewhat surprising that no polarity effect was observed. It would be of interest to know whether, in post-mortem examinations, any differences in the mechanism of failure were observed.

Dr. W. Vogel (Germany) (*communicated*): It was in 1929 that I first began to make a.c. voltage tests on the long-time breakdown strength of impregnated paper cables with d.c. voltage superposed. My tests were made with the same test arrangement as that described in Dr. Robinson's paper, and they gave similar results. The test results were not published at that time because we hoped that the superposing of d.c. voltage would result in an effect fit for technical use. It was anticipated that the effect of the d.c. voltage would be to produce in the dielectric a considerable mechanical pressure, which in its turn would cause a considerable increase of the breakdown strength under a.c. voltage. The German Patent No. 554966, of the 2nd August, 1929, was obtained to cover this idea. I share the author's view and explanation regarding the independence of the two sorts of voltage from each other when applied to a dielectric.

Dr. S. Whitehead (*communicated*): Dr. Brazier's paper is of particular interest to me, partly because an investigation has recently been completed on the subject of thermal instability by the Electrical Research Association, and also because a cable is an interesting case of thermal instability with the thermal resistance partly internal and partly external to the specimen. If the power factor or D.L.A. is large and independent of stress, and if the thermal resistivity of the dielectric is high, the critical or breakdown voltage is independent of the dimensions of a plane specimen and depends only on its specific energy losses, or the product of the D.L.A. and the permittivity, their temperature coefficient (assumed more or less exponential), and the thermal resistivity. This voltage is a constant of the material but is normally so high that other factors intervene before it is realized, except with insulators for very high voltages. In addition, if the D.L.A. varies with stress the formulæ are more complicated. Accordingly, the E.R.A. tested specimens with the thermal resistance outside the specimen; agreement was then obtained with the theoretical formulæ even though in nearly every case the D.L.A. varied with stress, particularly at higher temperatures, as is shown in Dr. Brazier's paper.

The case where the thermal resistance lies partly in and partly outside the specimen and where the D.L.A. varies with stress is peculiarly difficult, and Dr. Brazier's method—employing numerical and graphical approximation—is of great interest. It should be noted, however, that it is the variation of D.L.A. with stress which is the most serious difficulty. If the D.L.A. and permittivity are independent of stress then the critical voltage V_m for thermal instability may be expressed by the equation

$$\frac{V_m}{V_{om}} = f\left(\frac{P_e}{P_i}\right)$$

where V_{om} is the critical voltage for the same external thermal conditions but with the thermal resistance of the specimen neglected, P_e is the external resistance, and P_i the thermal resistance of the specimen. This result may be derived from Fock's analysis, and it is hoped to detail it in a later publication. As a cable is also a uni-dimensional problem, a similar expression applies. Now V_{om} is easy to compute, so that since the form of the function f is the same for all dielectrics having a D.L.A. independent of stress and a similar law of variation with temperature, V_m can be easily found from V_{om}. Even if the D.L.A. varies with stress and the equation given becomes untrue, it is not widely in error except for a large effect of stress compared with that of temperature. If the D.L.A. varies with stress one calculates V_{om} with the correct variation of D.L.A. with stress, which is not difficult, and when one deduces V_m therefrom by means of the equation given one is only concerned with an error in the ratio V_m/V_{om} which is often within permissible limits. For example, Dr. Brazier quotes the case of a cable with an internal resistance of 77 thermal ohms. If the external thermal resistance were 97 thermal ohms and if the D.L.A. were independent of stress and varied exponentially with temperature, the ratio V_m/V_{om} would be of the order of 0·75, i.e. there would be a reduction of 25 per

cent due to the internal thermal resistance (neglecting the core heating). If now we take an actual case where the D.L.A. varies with stress, V_{om} can be calculated directly from the curves of D.L.A. and we can assume that the ratio V_m/V_{om} is still about 0·75 as a first approximation. This method has been found useful with dielectrics having complicated variations with stress and temperature, and it would be of interest if it could be applied to cables to some extent. When the external thermal resistance was more than 10 times the internal thermal resistance the ratio V_m/V_{om} did not differ much from unity in most cases in our work.

We have found a difference parallel to that noted by the author between the decomposition products for thermal and non-thermal breakdown in organic dielectrics such as untreated papers, varnished silk and cloth, varnish pressboard, and cellulose acetate. We have, however, found that the puncture in single sheets for thermal breakdown although of similar size to those observed by the author is irregular in shape, whereas that produced by intrinsic breakdown or external discharges of very short duration is very small and, with clear dielectrics such as mica and cellulose acetate, shows internal surfaces of reflection when examined microscopically. If the external discharges are of longer duration more extensive and sometimes tree-like damage occurs.

Finally, it is of interest to note that the author finds with cables, as we have found with other dielectrics, that although breakdown may be sudden and local the breakdown voltage will nevertheless follow, under appropriate conditions, the laws of general thermal instability, without recourse to hypotheses (such as Wagner's) of filamentary or local instability.

The Authors' Replies to the Discussion.

Dr. D. M. Robinson (*in reply*): Mr. Scott quite rightly doubts the efficacy of V.T.B. testing as a criterion of cable suitability. The results set out in my paper are by no means confined to this type of test, and I did not intend to suggest that " the way to improve quality of cable is to concentrate on the elevation of the V.T.B. characteristic."

On the contrary, I have very little faith in the V.T.B. characteristic, except as an indication of factory excellence, and I am much more interested in the results of accelerated-ageing and long-time stability tests. When failure or partial failure occurs, it follows the same mechanism whatever the method of test, provided thermal instability is avoided, and the paper was intended as an account of the mechanism rather than a statement of the conditions under which it occurs.

In a further communication, dealing specifically with coring and tracking, it will be possible to give, as requested by Mr. Scott, some account of the mass of supporting evidence which has been accumulated.

The difference in performance of the 3-core and single-core cables quoted by the same speaker was in all probability due to the much lower pressure produced in the latter on cooling, owing to its better filling. (The filler spaces in a 3-core cable are seldom as completely impregnated as the cable dielectric.) The breakdowns are not due to cavitation within the cable wall, but to the formation of low-pressure voids adjacent to the conductor.

While I am in general agreement with Mr. Webb on the subject of waxing, it is necessary to point out that cables made with the best modern factory technique have shown only very slight waxing after a vigorous stability test (1 year, weekly cycles to 65° C., 1·1 and 1·5 times working voltage) followed by 100 hours at 3·5 times working voltage, and it seems therefore rather rash to regard waxing as " inevitable " in solid-type cable.

From the observed shapes and sizes of the wax deposits, it appears that the amount of gas produced by void-ionization is very small (see Section 11 of the paper).

The application, next to the conductor, of a thin layer of substance having a " long-time breakdown strength " greater than that of paper will, as Mr. Mildner suggests, raise the breakdown strength and permissible working stress of the cable considerably. Such a construction is the subject of a patent originating from our laboratories as a result of the work described.

I agree that in some cases the reduction of electric strength as a result of excessive stress may be due to the gas evolved, but in other cases it is undoubtedly true that as a consequence of the excess stress the spark discharge has already found its way between the fibres of the first one or two papers, although the carbon core cannot at that stage be detected by the microscope.

In reply to Mr. Bibby, it may be said that no evidence has been brought forward to show that the breaking-down of a weak spot by direct current causes damage to any other part of the system, however weak. In practice, a further d.c. test should always be made after the original breakdown has been removed, and this would serve to pick out any dangerous weak spot.

Mr. Hastie mentions the case of an oval cable in which the tracking took place more readily on the minor axis of the cable; I agree that this was probably due to the cable being softer on that axis. It is, of course, quite possible that the original coring in these cases took place on the major axis and then tracked around to the minor. The high-voltage failures were probably completed by thermal instability, being started by tiny tracking systems which were then burnt out by the fault.

Further work has been done on the transition from tracking to thermal failure subsequent to the preparation of the original papers. Records were kept of the " penetration " of the treeing, i.e. the number of papers from the conductor at which the outermost branch was found, in all cases where a tracking system eventually caused thermal breakdown in the manner shown by Fig. 12 of Dr. Brazier's paper. Fig. B shows for one type of cable the relation between the percentage penetration and the test voltage, and it will be seen that for the highest voltages the penetration becomes very small indeed, and is then liable to be completely burnt out by the fault. When this occurs, the origin of failure may be falsely attributed to thermal instability.

I can sympathize with Mr. Hastie when he finds it difficult to understand that the presence of an ionized region in the centre of the dielectric does not appre-

ciably affect the tracking breakdown, but our evidence certainly has been that the breakdown does not tend to choose portions of the cable in which the mid-dielectric cavitation has been severe. It is probable that the space charges set up by the ionization automatically regulate the stress layer by layer, so that the cavitation causes no increase of stress at the conductor.

In view of the first sentence of Mr. Hastie's second paragraph it is necessary to point out that the word "deterioration" throughout my paper is reserved for the combination of treeing, coring, and dryness, which always occurs in connection with tracking breakdown. Mid-dielectric waxing is not regarded as deterioration, as we have no evidence that it is harmful. The maximum deterioration and the maximum waxing may occur at a

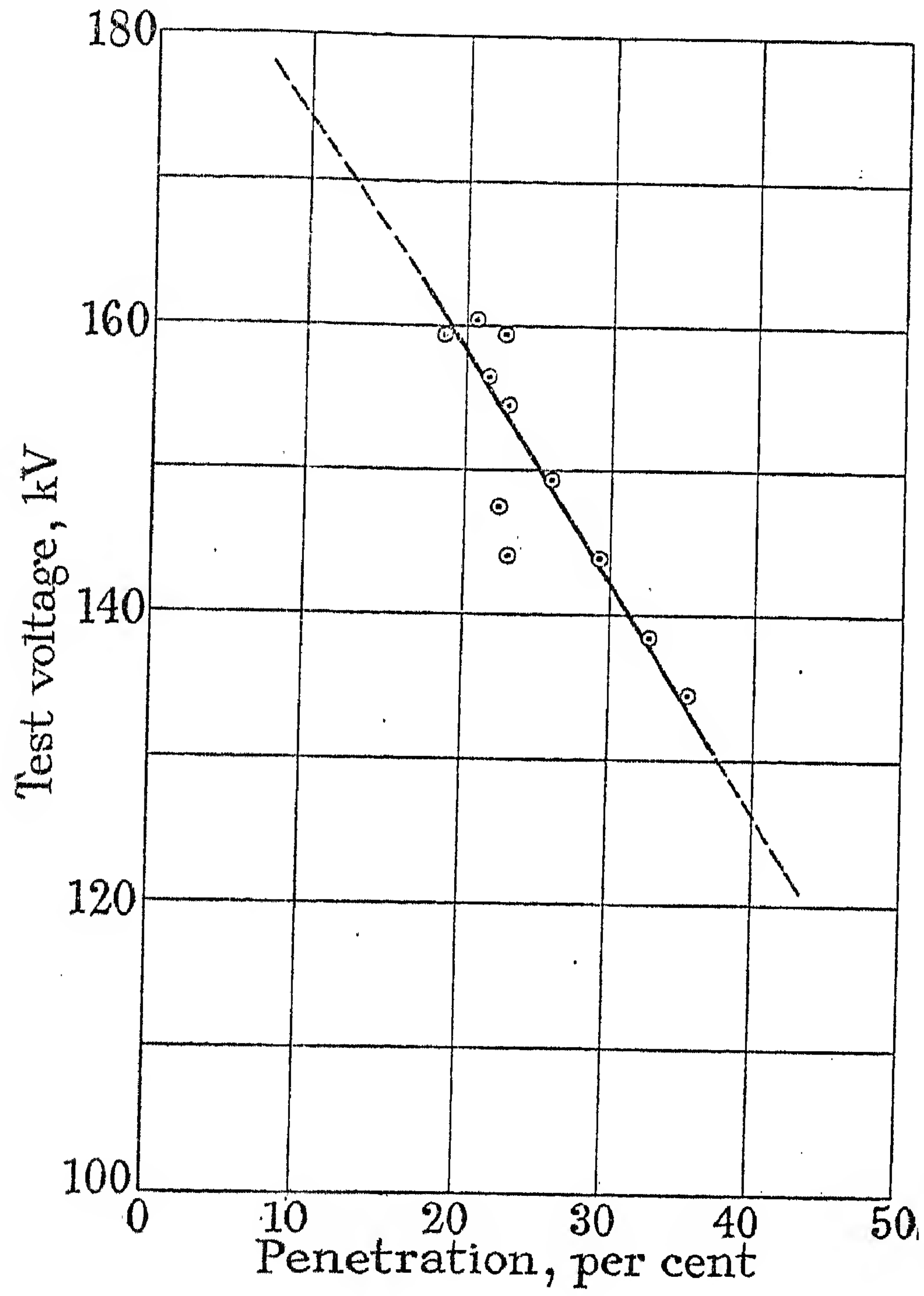


FIG. B.—Graph showing relation between penetration of treeing and voltage of test, for a 66-kV cable.

distance from the conductor, but, whereas the latter has no influence on the breakdown, the former is itself an advanced stage of failure.

Dr. Brazier and I at first shared Mr. Thomas's view that there ought to be some alteration of mechanism according to the direction of the superimposed d.c. voltage, but meticulous examination of the incipient failures in all the samples has failed to reveal any difference between the two cases, nor do these differ from the incipient failures in cables tested with alternating current only. The reason, as explained on page 97, is that the d.c. stress, once applied, does not cause any additional movement of ions and hence plays no part in the dynamic process of the tracking breakdown. It is interesting that Dr. Vogel has obtained similar results and shares the same opinion. Recently the d.c. voltage has been increased up to $5\frac{1}{2}$ times the alternating-current r.m.s. value without any change of breakdown time or of the mechanism.

I should like to congratulate Mr. Del Mar on the care he has shown in keeping his samples for over 10 years! It is very gratifying to know that he has been able to find the carbon cores and that they originated, as in our case, in the "channels between the edges of the first paper" or first gap. I appreciate his remarks about the permittivity of the oil, but of course, when a gas bubble occurs in the gap, precautions of this sort are no longer any use. I am in qualitative agreement with the remarks quoted from Dr. Osborne's paper.

Dr. L. G. Brazier (*in reply*): It is very gratifying that so many matters of considerable interest have been raised in the discussion.

Dr. Rayner and Mr. Webb ask about the importance of resin in producing a high D.L.A./temperature characteristic. I confirm that the curves given in the paper were obtained on a compound consisting of 23 per cent resin in a paraffin type of oil. I agree that the resin contributes largely, although not by any means entirely, to a bad D.L.A./temperature characteristic, but there are many difficulties in the way of a complete elimination of resin. The difficulty of obtaining a suitable viscosity/temperature characteristic without resin can be illustrated by Fig. C. The viscosity/temperature curve of compound without resin is always much flatter than that of compound with resin. Without resin, therefore, it is impossible, or at any rate very difficult, for the viscosity/temperature characteristic to be adjusted so that at impregnating temperatures of 120° C. or thereabouts the compound is sufficiently fluid to enable an easy and economic impregnation of the cable to be carried out, and at the same time at operating temperatures in the region of 20° C. the viscosity is sufficiently high to prevent drainage of the compound from the higher to the lower portions of the cable.

Dr. Rayner also asks whether, when measurements are carried out with the tuned Schering bridge, sufficient account is taken of the energy contributed by harmonics of the fundamental frequency. It seems likely that the difference between these two cases would only become important when the wave-form of the testing voltage was very impure. The work described in the paper has been carried out with alternators specially designed to give a pure testing wave-form. It may be taken that no harmonic exceeds a magnitude of 1 per cent of the fundamental, and in these circumstances energy loss due to harmonics is extremely small.

Mr. Scott asks for information about the role of moisture in producing thermal-instability failures. I regret that I have not had an opportunity of examining this case. Trouble due to moisture is a very infrequent occurrence in cables of the highest voltages. So far as moisture is known to increase the D.L.A./temperature characteristic, however, it will undoubtedly promote a likelihood of thermal-instability failure.

Mr. Main suggests that the high D.L.A./temperature characteristics described in the paper will not be exhibited by pressure cables. The question of pressure application does not, however, in fact, appear to be relevant to the question of D.L.A./temperature characteristic. Our own tests have shown definitely that the

application of pressure does not affect either favourably or adversely the D.L.A./temperature characteristic. This, of course, refers to ordinary well-manufactured modern cables in which there is no appreciable gaseous ionization. Naturally, any gaseous ionization will be suppressed by pressure. As a matter of fact, many of the examples given in the paper refer to pressure cables—using the term to describe any cable in which gaseous ionization is extinguished by the application of pressure, and not restricting the term in the way that Mr. Main and Mr. Hochstadter would like it restricted.

Mr. Main, Mr. Bibby, and other speakers, suggest that the examples given in the paper compare so unfavourably with cables of modern manufacture that the question of thermal instability for these modern cables is still a matter

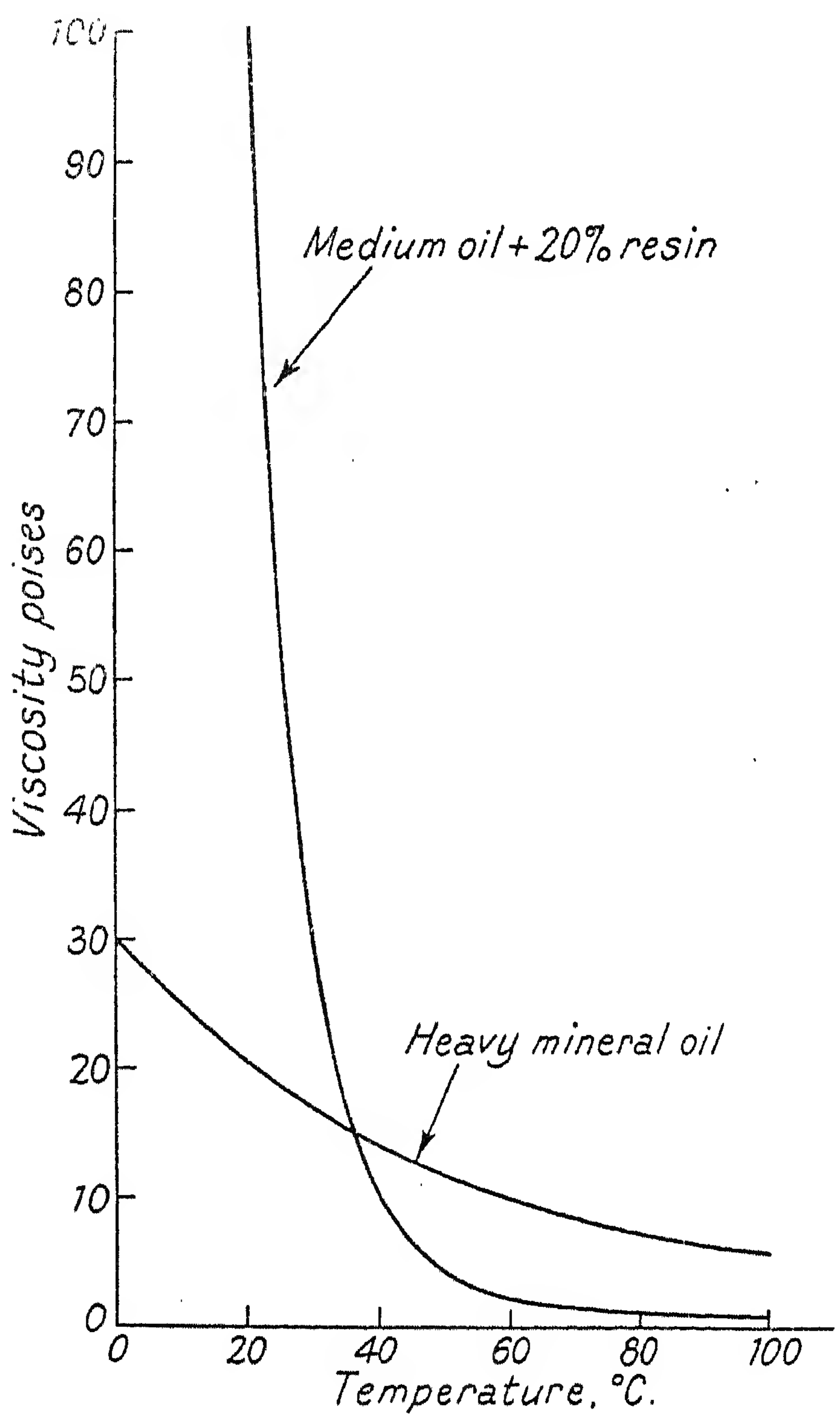


FIG. C.—Viscosity/temperature curves.

of somewhat academic interest. A number of opportunities have presented themselves for examining the D.L.A./temperature characteristic of most of the "solid" type 66-kV feeders recently installed in London. None of the dielectrics so examined, however, could be put forward for a 132-kV feeder if a type test had to be carried out consisting of heat cycles on the buried cable in trefoil formation at a test voltage of 1·5 times working voltage, because of the intervention of thermal instability. In these circumstances, it does not appear that the subject is of that academic interest which is suggested.

I am indebted to Dr. Starr for improving the demonstration that thermal instability under certain conditions is independent of the shape or size of the dielectric. I welcome also his discussion of various methods of computing and exhibiting the thermal-stability results, some of which are, in fact, adumbrated on page 105 of the paper.

Mr. Stevens raises the extremely pertinent question of the definition of factor of safety for dielectrics where there is any risk of thermal instability. If dielectrics are to be used in which this risk is present, then it will probably be desirable to control the overall factor of safety by specifying testing margins on the voltage, conductor temperature, and external thermal resistance. It is to be hoped, however, that dielectrics will be produced in which the risk of thermal instability is sufficiently remote to avoid the necessity of setting up an exact factor of safety.

Mr. Hastie describes a transition on the same cable from failures of the tracking type with long-time testing, to thermal-instability failures with short-time high-voltage testing. This is a case of very great interest, which I have not myself had an opportunity of observing.

Mr. Hochstadter appears to consider that the work and results described in the present paper are already adequately covered by publications of his own and of other writers; and he joins with other speakers already mentioned in suggesting that in any case the subject is of academic interest only in relation to modern cables. No one engaged in the cable industry is likely to under-estimate or undervalue the contributions which Mr. Hochstadter has made to electrical transmission; but, after a careful study of all the papers to which reference is made, it still appears from the prejudiced viewpoint of the author that the present paper breaks new ground, not covered by the earlier publications. It is a point, however, which can suitably be left to the judgment of those who are sufficiently interested to compare the various papers.

In his 1933 paper,* to which reference is made in the present paper, Mr. Hochstadter describes experiments on thermal instability. The experimental technique is open to obvious criticisms. The heating of the cable was carried out by means of a small heater covering only a few inches of the cable, no allowance being made for the longitudinal dissipation of heat along the sheath and along the conductor. Moreover, in discussing his experimental results he does not make use of the method of analysis described in the present paper, or of any similar or corresponding method. Thus he makes no allowance for the increase of external thermal resistance when the cable is operated in trefoil formation or for the increase due to burying the feeder. It is pointed out in my paper that these effects may easily result in a tenfold increase of the external thermal resistance. As a general result, Mr. Hochstadter reached the conclusion that "there is no doubt that even this thickly insulated cable at such a high electrical stress (350 kV per cm) . . . is still thermally very stable." As a matter of fact, it can be seen from Fig. 4 of Mr. Hochstadter's paper that the stability is solely due to the artificially high dissipation from the cable under the particular test conditions; that is to say, when the cable is tested as a single cable exposed in the laboratory. The actual value of the external thermal resistance is in the neighbourhood of 50 thermal ohms. If the same cable is tested in trefoil formation and buried, the external resistance will be many times this value; and from the same diagram it can be

* *Elektrotechnik und Maschinenbau*, 1933, vol. 51, p. 218.

seen that it is only necessary to increase the external thermal resistance to 120 thermal ohms and the cable will go into thermal instability at 350 kV per cm without carrying any useful load on the conductor.

It is quite true that Mr. Hochstadter was strictly discussing the character of his high-voltage test results, but his phraseology appeared to suggest that there was at these high voltages still a very comfortable margin for the useful operation of the cable; which is, in fact, not the case.

Dr. Whitehead's observations are of very great interest. It is a great misfortune that any general treatment of the subject, such as that described by the formula which he gives, must apparently be restricted to the special case where the D.L.A. does not vary with the stress, and is not, therefore, applicable to the case of cable dielectric.

CONTINUOUSLY EVACUATED VALVES AND THEIR ASSOCIATED EQUIPMENT.

By C. R. BURCH, B.A., and C. SYKES, Ph.D., M.Sc.

(*Paper first received 27th September, 1934, and in final form 21st May, 1935; read before the* WIRELESS SECTION *6th February*, 1935.)

SUMMARY.

This paper describes demountable thermionic valves evacuated continuously by means of oil condensation pumps.

TABLE OF CONTENTS.

(1) INTRODUCTION.

The idea of a continuously evacuated thermionic valve is as old as the art of valve making, for every valve is continuously evacuated unless and until it is sealed off from the pumps. The additional idea of making such valves demountable was originated during the War by A. K. Macrorie, C. L. Fortescue, G. B. Bryan, and H. Morris Airey;* and indeed experimental work on continuously evacuated valves of this type was carried out both during and after the War by H.M. Admiralty. Mercury pumps, at that time the standard pumps for high-vacuum work, had to be used in conjunction with continuous supplies of liquid air or solid carbon-dioxide. In this way, the mercury vapour given off from the pumps was frozen and thereby prevented from reaching the valves. The necessity for such refrigerants so negatived the advantages associated with demountability that the experiments were discontinued on the successful introduction of silica valves for naval wireless-telegraph purposes.

We do not read of demountable valves in practical use until 1927, when C. F. Elwell† described the Holweck demountable valve and the Holweck rotary molecular pump which is used to exhaust it. This pump produces the high vacuum necessary in a thermionic valve without the help of either liquid air or solid carbon-dioxide.

Demountable-valve development, in fact, had had to wait for developments in vacuum technique. It was natural, therefore, that a further development, the discovery of the possibility of operating a condensation pump without the necessity for expensive refrigerants, should form the starting point for another attack on the demountable-valve problem, and lead to the development of the valves and associated apparatus described in this paper.

* British Patent No. 162367. † *Journal I.E.E.*, 1927, vol. 65, p. 784.

(2) DEVELOPMENT OF LOW-VAPOUR-PRESSURE OILS AND GREASES.

Condensation pumps possess the property that whilst they can reduce the pressure of permanent gas to a negligible value, they cannot reduce the pressure of the vapour of their own working fluid below that corresponding to the vapour pressure of the fluid at the temperature of the water jacket of the pump. A mercury condensation pump, for example, without any "cold" trap, will reach a total pressure of $0 \cdot 001$ mm, of which quite a negligible part, say 10^{-9} mm only, may be due to permanent gas such as air. The remainder will be due to mercury, $0 \cdot 001$ mm being the vapour pressure of mercury at the temperature of the water jacket of the pump. Solid carbon-dioxide dissolved in acetone produces a temperature of $-78°$ C., and at this temperature the vapour pressure of mercury is 5×10^{-6} mm: at the temperature of liquid air ($-190°$ C.) the vapour pressure is quite negligible. The use of a "cold" trap, containing either of these refrigerants, placed between the mercury pump and the valve to be evacuated, thus enables a much higher vacuum to be obtained; in fact, a vacuum sufficient for the usual type of power valve, i.e. 10^{-5} mm or less.

It had long been realized that if we could find a liquid capable of being boiled at reduced pressure without decomposition, but about 1 000 times less volatile than mercury, then a condensation pump using such a liquid as a working fluid would produce a vacuum of about 10^{-6} mm without the help of refrigerants, and would be quite adequate for valve exhaustion.

In 1929 one of the present authors* carried out some experiments on the distillation of lubricating oil in a molecular still. In such a still, the mean free path of a vapour molecule in residual gas is large compared with the distance between the evaporating and condensing surfaces, so that distillation occurs substantially as it would were the still evacuated perfectly. It was observed that the temperature necessary to produce a distilling speed corresponding to a vapour pressure of $0 \cdot 001$ mm rose steadily during the course of the distillation from a little over room temperature to 350° C. In other words, lubricating oil contains constituents which must be heated to temperatures varying from room temperature to 350° C. to develop the same vapour pressure as that of mercury at room temperature.

A molecular-still "fraction," less volatile than mercury by 120 deg. C., may be expected to have a vapour

* C. R. BURCH: *Proceedings of the Royal Society*, A, 1929, vol. 123, p. 271.

pressure at room temperature of about 10^{-5} mm. If this would stand boiling at the $0 \cdot 1$ mm or so necessary in the vapour blast of a condensation pump without decomposition, one could clearly expect a vacuum good enough for thermionic work with water cooling only. The more volatile fractions were therefore distilled off and the least volatile fractions also rejected, since they could not be expected to boil without decomposition. An attempt was then made to exhaust a 150-watt valve on a condensation pump using as working fluid a "medium fraction" made in the molecular still from lubricating oil. The "backlash ratio," i.e. (Positive ions to grid)/(Electrons to anode), fell to a value less than is usual for sealed valves of this type, and so the possibility of an oil condensation pump was proved.

The normal process used in the refining of lubricating oil involves a distillation at a pressure of a few millimetres, and a certain amount of thermal decomposition ("cracking") always takes place. This produces new volatile constituents, which, even though present in very small quantities, raise the vapour pressure of the oil thousands of times. In the molecular still, however, the distillation takes place at temperatures so low that thermal decomposition does not occur, and thus provides a method of obtaining the less volatile fractions of the oil free from "cracked" products.

The vacuum problem of a demountable valve involves, however, more than the provision of a convenient high-speed pump. It requires a jointing material the vapour pressure of which is very small, since it is not possible—even with such a pump—to reach a pressure much less than the saturation pressure of any jointing material which may be exposed to the vacuum. For example, suppose the exposed area of the jointing material is A cm², and the molecular weight M; then $10A\sqrt{(30/M)}$ litres of vapour at the saturation pressure p_s of the material will be produced per second. If the speed of the pump be S litres per second for air, its speed for vapour of molecular weight M is $S\sqrt{(30/M)}$, so that the ultimate pressure which the pump can produce will be limited to

$$\frac{10A}{10A + S} p_s$$

Thus a pump having a speed of 20 litres per sec. can reach a pressure only 3 times lower than the saturation pressure of the jointing material, if 1 cm² thereof is exposed. This pressure will persist until the whole of the jointing material has been pumped away as vapour: this means in practice that it will persist indefinitely.

Fortunately, substances exist which have mechanical properties suitable for jointing compounds, and at the same time negligible vapour pressure at room temperature. Such substances remain as undistillable residues when petroleum jelly or bitumen are distilled as completely as possible in the molecular still. Their mechanical properties are in some cases improved by blending with a non-volatile filler.

To the low-vapour-pressure materials produced in the molecular still the authors have given the name "Apiezon products."*

* From α (privative) and πιεζον (pressure).

(3) Design and Properties of Oil Condensation Pumps.

Not every condensation pump designed to use mercury will operate as a pump with oil as the working fluid, and it has been found necessary to design pumps to suit the oil. A section of such a pump (Type O_3) is shown in Fig. 1. The electric heater, A, of 350 watts, boils

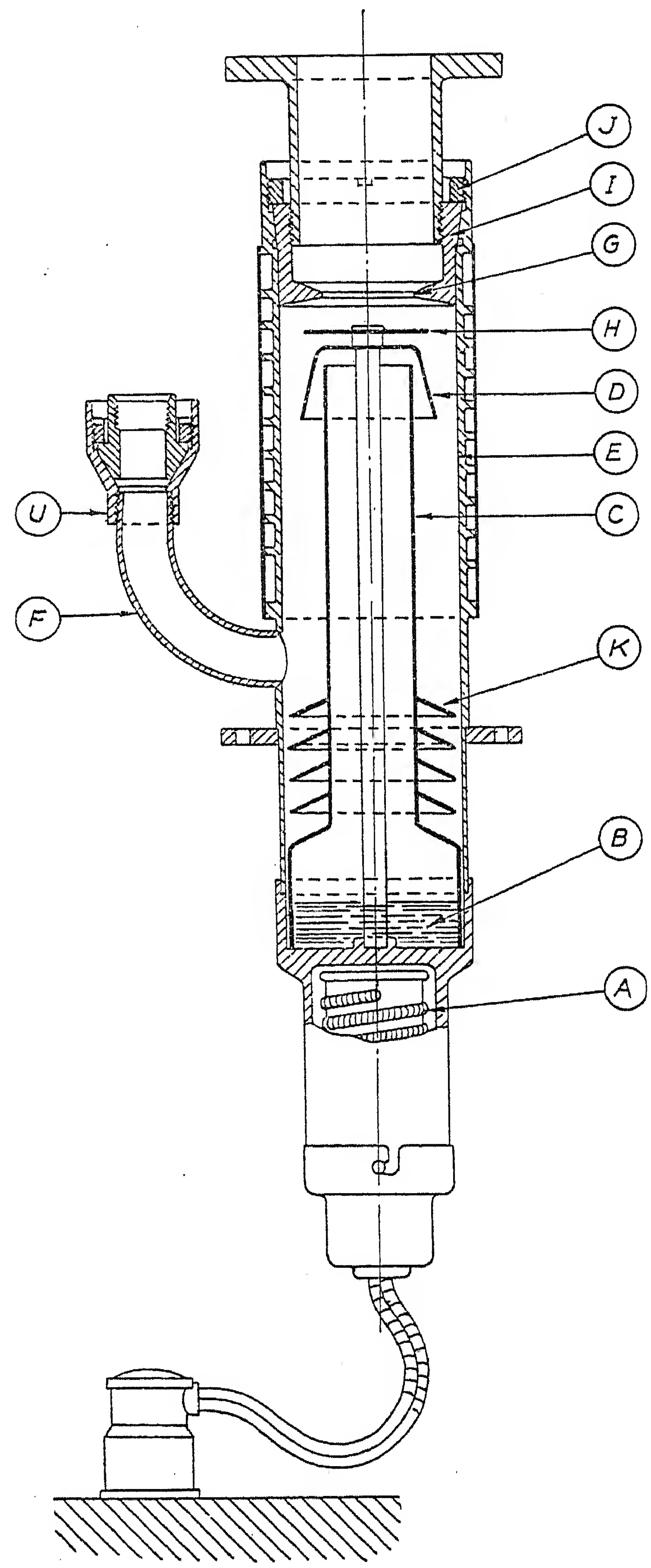


Fig. 1.—Type O_3 condensation pump.

the oil in the boiler part B of the pump at a pressure of $0 \cdot 1$ to $0 \cdot 2$ mm. The vapour issuing from the uptake pipe, C, is deflected by the cowl, D, to form a blast downwards. This strikes the water-cooled condensing surface at E, and carries with it those gas molecules which happen to enter the vapour blast. The condensed oil runs back to the boiler, so that the process is continuous. The fore-vacuum pipe, F, is connected to a

pump producing a vacuum of 0·1 mm or less. This mode of action is, of course, exactly the same as that of any mercury condensation pump. The oil condensation pump is of special design in the following respects.

The Baffle.

The mouth of the pump is constricted at G, and below this constriction there is supported on top of the cowl a disc, H. The arrangement is such that a straight line drawn from any point in the vapour blast cannot pass out of the mouth of the pump without being intercepted. It is essential that this condition should be satisfied; otherwise oil molecules having a velocity in the upward direction produced by multiple collisions in the vapour blast, could, in the absence of the baffle, pass directly into the system under exhaust. This transport of molecules is independent of re-evaporation, and can take place even if the vapour pressure of the liquid at the condensing surface is zero. In this way the surface of a valve could be coated with a layer of oil even though the oil had a very low vapour pressure at room temperature. Such an occurrence has, for example, been observed using a pump without a baffle. The necessity for a cold baffle, whatever the working fluid, appears to have escaped notice as long as mercury was the only fluid used, and, in general, vacuum textbooks recommend that no constriction be placed above the cowl. In the case of mercury, the amount of vapour leaving the vapour blast in an upward direction is less than the amount which passes up through the mouth of the pump owing to re-evaporation from the condensing surface. Consequently a water-cooled baffle is not sufficient. The cold trap, usually a separate unit, deals effectively with the vapour arising through both causes. With regard to the oil condensation pump and baffle described, the point may be raised that multiple collisions can occur in the annular space between the cowl and baffle and enable some oil molecules to pass round the baffle without hitting it, and the question arises how many baffles should be provided. Clearly, the number of baffles should be so chosen that the number of oil molecules traversing the system as a result of multiple collisions is smaller than the number due to re-evaporation from the baffle system. In practice, it appears that the baffling system described is adequate. The baffle is conveniently attached to the pump by means of the conical ground joint, shown at I, which is forced home by the nut, J. It is flooded with oil of the same type (Apiezon B) as is used in the pump, so that gas leakage is impossible. In cases where the pump is incorporated in a permanent pumping equipment, the conical joint is sealed with bitumen Apiezon (Type KW).

The Cowl and Uptake Pipe.

Since the oil will decompose if boiled too strongly, the supply of oil vapour available is limited, and it becomes important that heat losses from the cowl and uptake pipe should be made up as far as possible by heat conduction from the base of the pump, and not by condensation of oil vapour. For this reason, the cowl is supported on a copper rod, silver-soldered into the copper base of the pump, and is centred by a spider of thin steel rods. The uptake pipe is made of copper and fitted with baffles, K, to prevent a strong vapour blast from travelling upwards from the hot oil around the foot of the uptake pipe.

The body of the pump is made from a copper-nickel alloy. This prevents corrosion of the water jacket, a very important feature, and also helps to diminish heat conduction from the boiler to the water jacket.

The fore-vacuum pipe is fitted with a conical union, U, which is oil-sealed externally; this, together with the conical joint at the top of the pump, enables the pump to be speedily removed from any pumping equipment when desirable.

Performance.

The pump will work against a fore-vacuum pressure of 0·05 mm, and will produce under suitable circumstances a limiting pressure of about 10^{-6} mm as measured on an ionization gauge calibrated for air. The pumping speed for air at any pressure below 10^{-3} mm, and high compared with the limiting pressure, has been measured and found to be 20 litres per sec.

High-backing-pressure Oil Condensation Pump.

The authors have not found it possible to make an oil condensation pump which will work against a fore-vacuum pressure of more than about 0·4 mm. In the first place, if the oil is boiled at a pressure sufficiently high for this purpose it decomposes, and in the second place when the minimum gap between the cowl and the condensing surface is reduced below about 2 mm (a condition necessary in a pump having a high backing-pressure) a film of oil bridges the gap and stops the pumping. This latter difficulty arises owing to the fact that oil wets the condensing surface.

By using the somewhat more volatile Apiezon A oil, and by cascading two suitable jets together in one pump, the authors have produced a pump, Type O_2, capable of working against a fore-vacuum pressure of 0·4 mm. This provides a large margin of safety on the performance of any reasonable mechanical pump.

The speed of the O_2 pump is 2–4 litres per sec., and its limiting pressure about 10^{-5} mm. The authors' normal practice is to cascade the O_2 and O_3 pumps. There is no risk of decomposition in the O_3 pump, and any slight decomposition in the O_2 pump cannot affect the final vacuum produced by the O_3 pump. The fore-vacuum pipes of both pumps are not water-cooled, so that the products of decomposition can be the more readily removed. The volume of oil in the liquid form lost from the pumps owing to this cause is negligible.

In connection with the operation of the pumps, it is desirable to ensure as far as possible that the heaters are not energized when the fore-vacuum pressure is higher than 0·4 mm, otherwise the oil becomes superheated to a certain extent and tends to be decomposed. Rises of pressure over short intervals are not detrimental, and in the case of a large leak starting during operation it is sufficient to switch off the heaters until the leak has been sealed.

Mechanical pumps will not pump water vapour, and it is necessary to remove this by chemical means from

the fore-vacuum system. Phosphorus pentoxide is used for the purpose, and a few grammes of this substance last for several weeks.

Taps.

To enable the various parts of a pumping plant to be shut off from one another and from atmosphere, some form of tap is essential. Taps for use on demountable-valve plant must give absolute reliability over long periods. In conjunction with the Audley Engineering Co., Ltd., the authors have developed the metal tap shown in Fig. 2. The tap comprises two ports in a flat steel disc, which are connected or disconnected

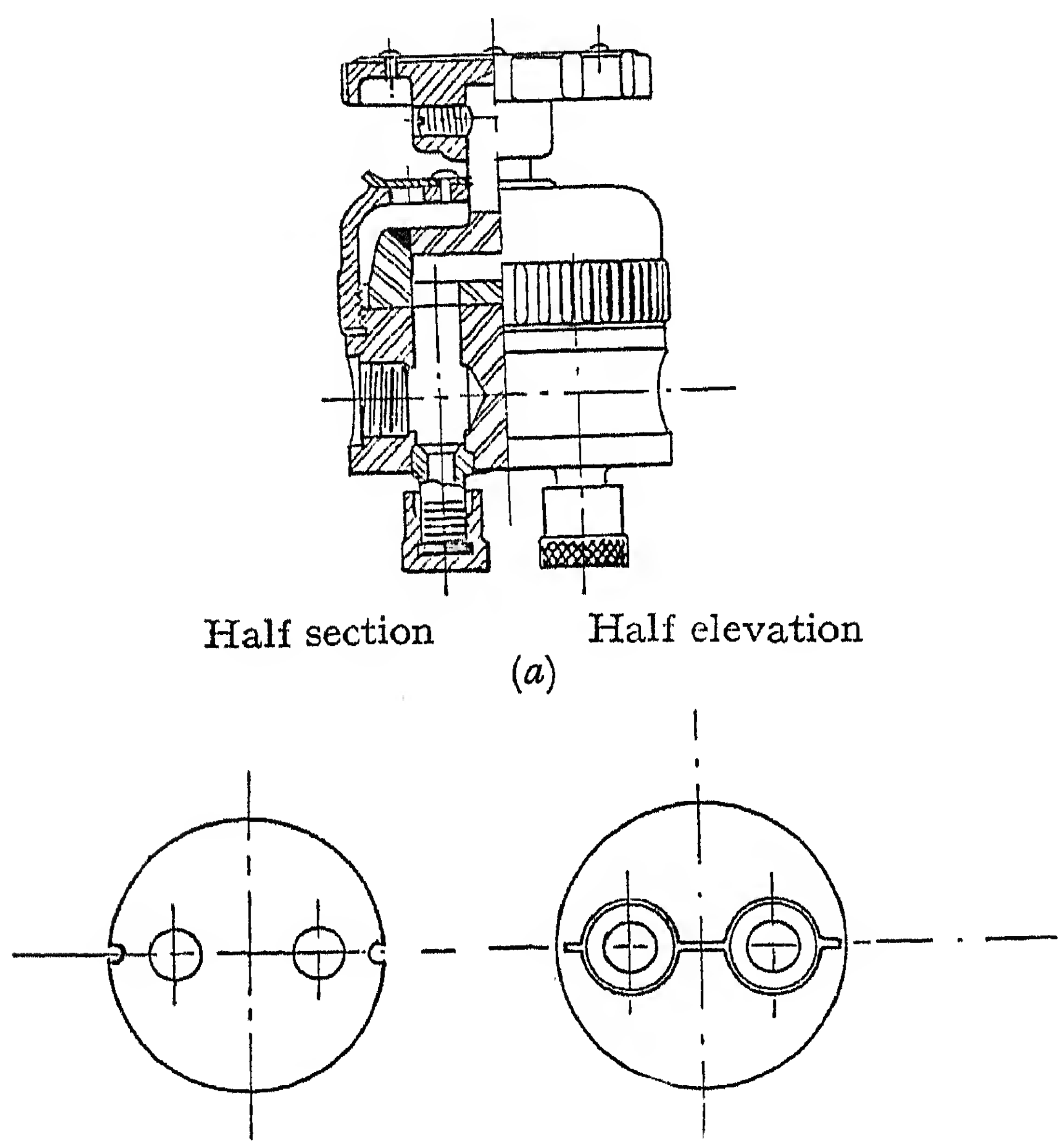


Fig. 2.—Metal tap. The lapped faces and oil-sealing grooves are shown in (*b*).

by turning a fitting flat disc carrying two transfer ports. Grooves are cut in figure-of-eight fashion around the fixed ports, and co-operative grooves are cut in the moving member containing the transfer ports, so that, in the closed position, the groove in the moving member connects the groove in the fixed member with the oil bath in which the moving member turns. Thus each port is completely surrounded by a groove filled with oil at atmospheric pressure when the tap is shut, and gas leakage is not possible. The first effect of turning the tap is to break the connection between the two systems of grooves, so that at no stage is the oil bath connected, via the grooves, to the vacuum. The two flat discs are lapped flat to within a few wavelengths of light, so that the rate of leakage of sealing oil into the vacuum is extremely small. It is sufficient to empty the sumps, with which the tap is provided, once a year or even less frequently. The sumps are sealed by means of screwed caps containing leather washers, and are flooded externally. The Apiezon oil J, which is fairly viscous, is used as sealing oil in the taps.

Joints.

We have already discussed the importance of jointing material in vacuum equipment. The correct design of joint is also important if a high ultimate vacuum is desired. Ground joints sealed on the outside are most satisfactory, since the rate at which the vapour of the jointing material can enter the evacuated equipment is limited by the small cross-section of the path afforded by the joint. The authors use flat ground joints in the valve, and prefer them to conical joints because (*a*) there is no risk of cracking either of the members of a flat joint owing to differential thermal expansion, and (*b*) it is easier to make interchangeable flat joints than conical joints. The "fit" of the joint is made as good as possible using reasonable care, and all members of proud joints are ground flat to within one or two wavelengths of light. Sunk joints are lapped with flat-ring laps until they show a uniform finish. Special care is taken with the demountable joint.

The joints are always assembled dry and evacuated to a pressure of 1 mm or less before jointing material is applied to the outside. It is easier in this way to put the joint together free from grit; in fact, the vacuum obtained with the joint dry gives an indication as to whether the joint is free from grit. There is, of course, no point in deliberately putting jointing compound between the faces. Flat joints should always be parted by leverage between appropriate parts of the joined members, and not by sliding, otherwise the surfaces may

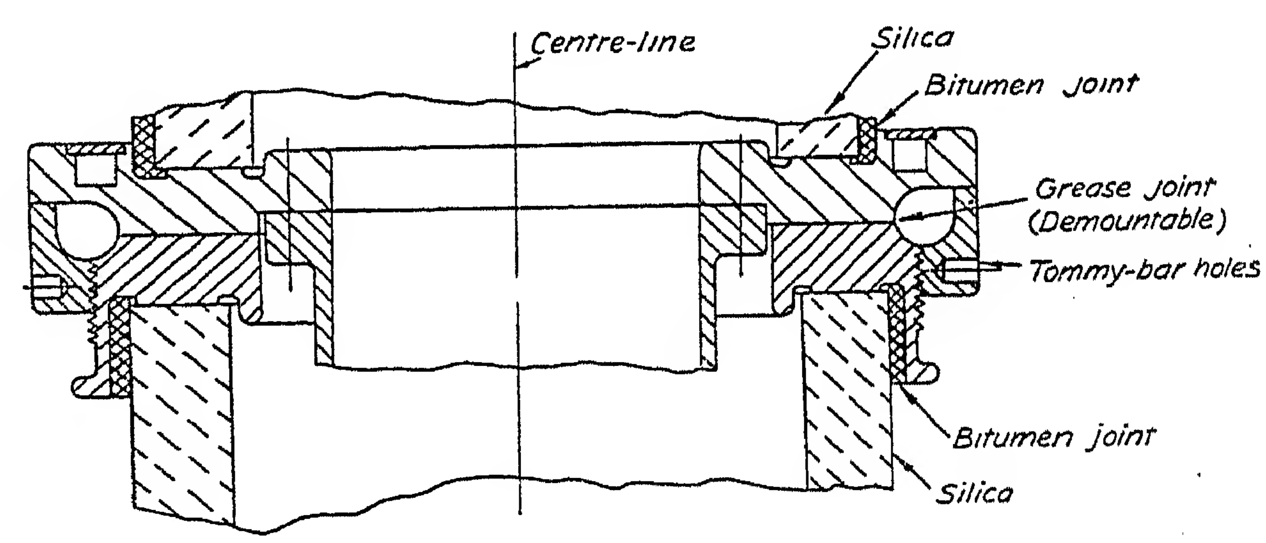


Fig. 3.—Arrangement for breaking demountable joint.

tear each other. A convenient method of doing this is incorporated in the valve in certain circumstances (see Fig. 3).

(4) Pumping Equipment.

One very great objection to pumping equipment in the past has been its fragility. It was realized in the very early stages of this development that any pumping equipment likely to find favour in industry must embody a minimum quantity of glass, and that the various parts must be of such a design that they can be assembled using ordinary engineering tools. With this idea in mind, the authors developed the metal pumps and taps already described, and these are connected together using copper piping and conical unions.

Fig. 4 shows diagrammatically a pumping plant suitable for one or more valves. The unions are marked "U" and the taps "T." P represents the phosphorus-pentoxide trap. The drying agent is held inside a removable nickel tray, and the trap is sealed with a glass lid so that an inspection can be made whilst the

plant is in operation. The arrangement of taps in association with the reservoir, R, enables the drying agent to be changed also with the plant in operation if this becomes necessary.

The equipment is fitted with discharge tubes, D, which are energized by a small induction coil. These tubes are useful for tracing leaks and in the initial stages of pumping from atmospheric pressure. When the valves are in operation the vacuum is such that none of the tubes show any discharge; i.e. the pressure on the fore-vacuum side is less than 5×10^{-3} mm. The

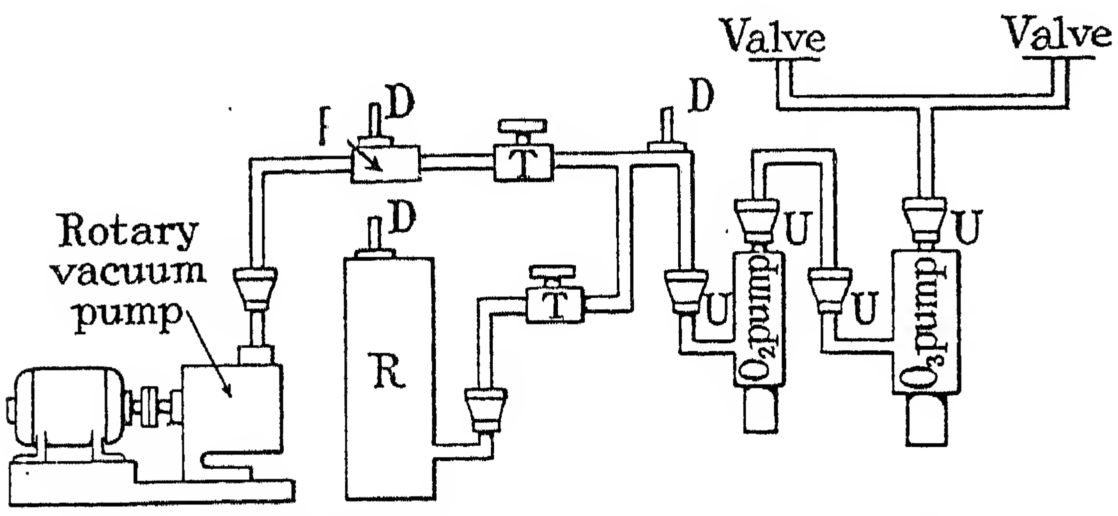


FIG. 4.—Schematic diagram of pumping plant.

pumping speed of the O_3 pump is about 50 times that of the rotary pump, so that any small but persistent gas evolution above normal at once shows up as a discharge in the tube on the fore-vacuum side immediately before the rotary pump. The general lay-out of such a pumping plant will be seen from Fig. 5, which is a photograph of a combination similar to that shown diagrammatically in Fig. 4.

The authors have developed a robust type of vacuum relay (see Fig. 6) which makes use of the same principle as the Pirani gauge, namely that the thermal conductivity of a gas depends on its pressure. A bimetallic strip, A,.is supplied with a constant amount of electrical energy, and in consequence its temperature varies with the gas pressure. The free end of the strip carries a

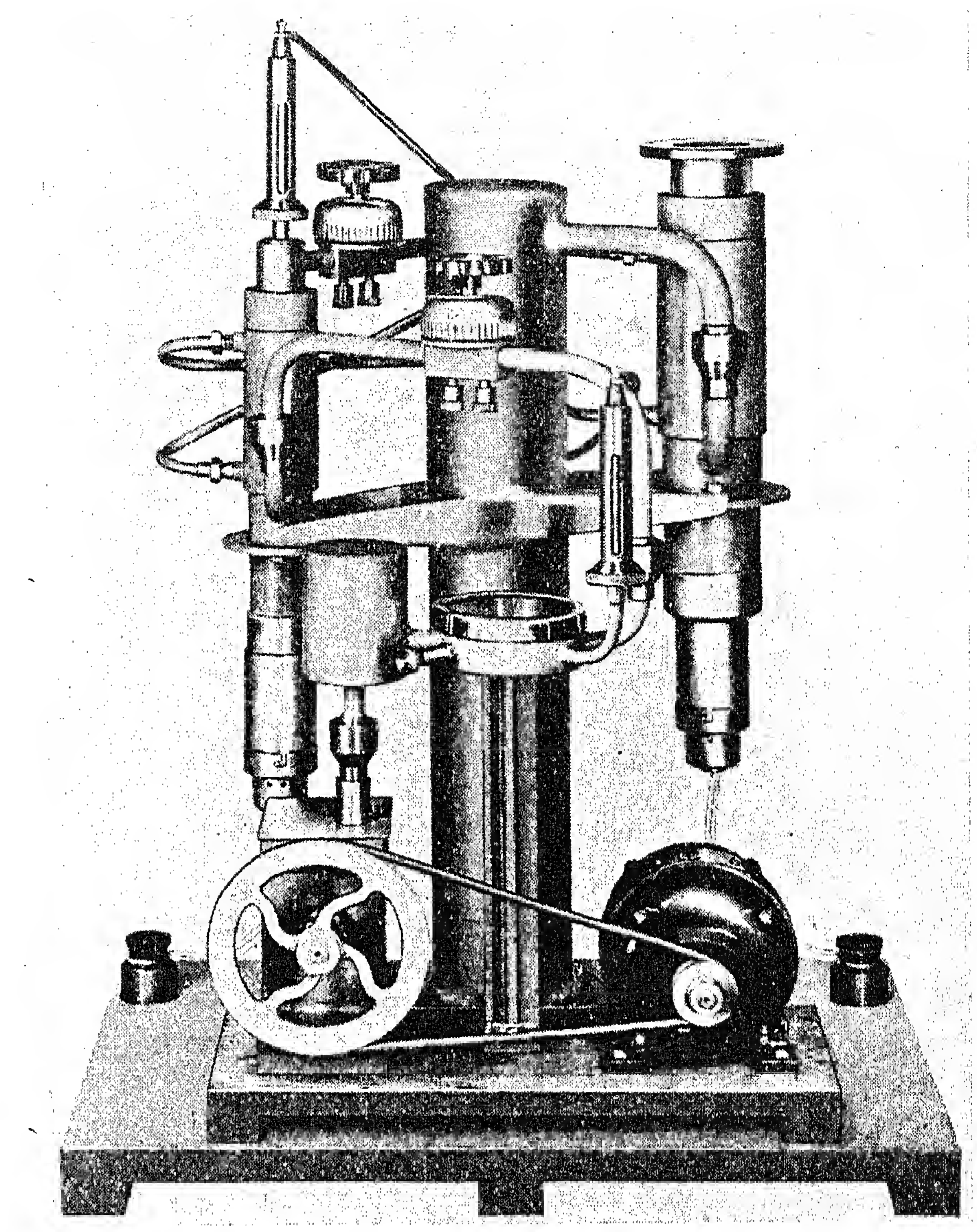
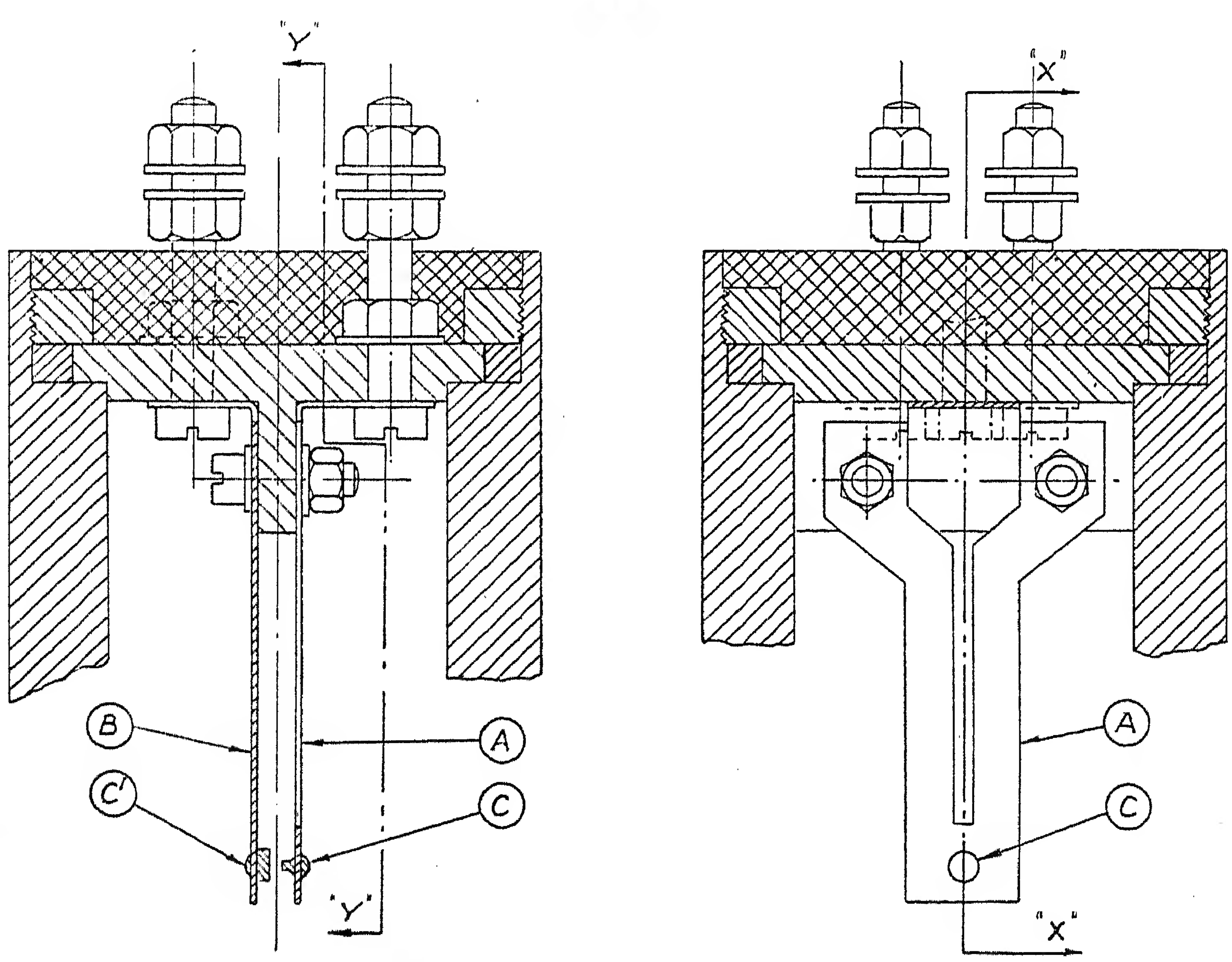


FIG. 5.—Pumping plant.

contact, C, which at the appropriate pressure touches another contact, C′, on a second bimetallic strip, B,



Section on line 'X-X' *Section on line 'Y-Y'*

FIG. 6.—Vacuum relay.

which is not heated. By suitable variation of either the power input to the strip or the contact distance at room temperature, the contacts can be made to operate at pressures between 0·05 and 0·4 mm of mercury.

By interlocking such relays with an electrically-operated lever system the taps can be opened or closed at certain desired pressures. In a similar manner the pumps can be switched on only when the fore-vacuum pressure is adequate, i.e. 0·4 mm or less. In the event of a leak sufficiently large to spoil the fore-vacuum to this extent, the pumps are immediately switched off and thus decomposition in the oil is avoided.

Thermal strips fitted to the condensation pumps are used to give a definite indication as to when the pumps are at the correct working temperature, so that the operator cannot light the filaments too soon.

During normal running conditions the amount of gas released from the valve is very small, and experiments have shown that if the evolved gases are allowed to collect in a reservoir of about 5 litres capacity (e.g. R, Fig. 4) the rate of pressure-rise is so small that only after 12 hours does it become necessary to re-evacuate the reservoir with the mechanical pump. Consequently trouble with the mechanical pump, if of a temporary character, can be cured without the pumping plant being put out of commission. Alternatively, the use of suitable control circuits enables the evolved gas to be pumped into the reservoir and the mechanical pump brought into operation occasionally to re-evacuate the reservoir.

To sum up, pumping plant has thus been constructed in which it is merely necessary for the operator to press a button to energize the equipment; the various relays open the taps, switch on the pumps in the required sequence, and give a visual indication when the plant is ready for use. Naturally any fault on the apparatus, such as, for example, lack of water through the pump jackets, vacuum failure, or heater failure, are also shown up on an appropriate indicator. The general rigidity of the equipment and its simple construction ensure that very little trouble is encountered in practice. This, together with the automatic features described above, enables the equipment to be operated by persons who have not had an extensive training in vacuum physics.

(5) Arrangement of Valve Electrodes and Insulation.

In a sealed-off valve the leads to the various electrodes are taken through the envelope by some form of metal-to-glass seal. When such a permanent joint is no longer essential the arrangement of the parts with respect to the envelope may be modified to facilitate assembly. The type of joint preferred by the authors, and described as the flat ground joint, lends itself to the type of valve construction shown in Figs. 7A, 7B, 7C, and 7D, which are sectional drawings of a 3-electrode valve, Type 330A. Such a valve will take an input of 50 kW at 10 000 volts on a wavelength of 10 m with reasonable efficiency.

The filament is fitted into a base B (Fig. 7A), which can be screwed into the filament leads (Fig. 7C). These consist of a solid copper rod, R, and a concentric tube, T, which are connected to the two copper filament flanges, R′ and T′. A short tube S_1, of either porcelain or silica, is used to insulate the flanges one from the other. The active part of the grid, G, is mounted in a copper base (Fig. 7B), which is connected by means of screws to the grid tube, C. The grid flange, C′, is insulated from the lower filament flange, T, and the anode flange, A, by means of suitable lengths of insulating tubing, S_2 and S_3. The various flanges contain water-cooling passages so that the joints can be kept cool.

After grinding, the flanges carrying the filament and grid, together with the necessary silica or porcelain tubes

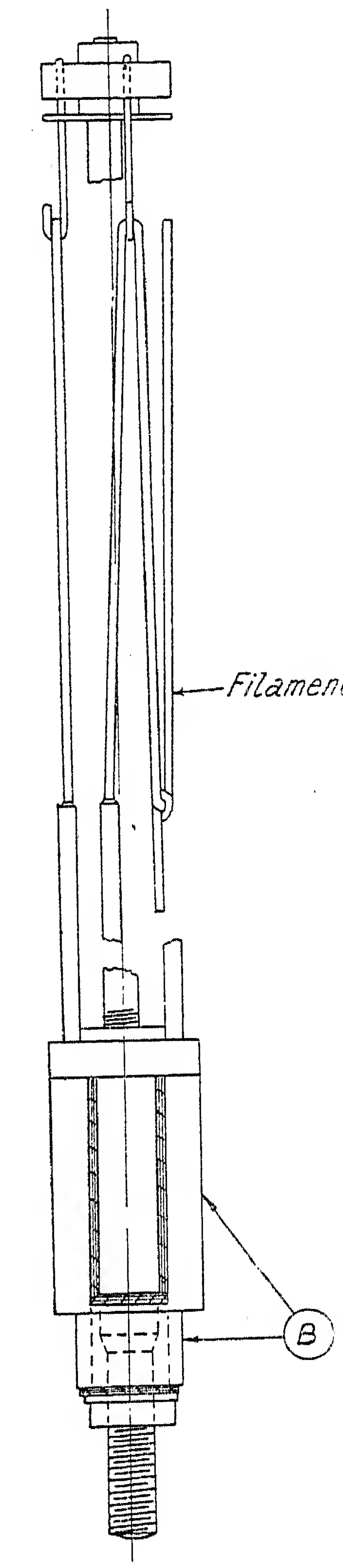


Fig. 7A.—Filament assembly.

(the complete structure, shown in Fig. 7C, is called the "head"), are assembled together and lightly clamped. The head is then evacuated and steam is passed through the water-cooling channels until the joints can be readily sealed with Apiezon W. At room temperature the strength of the joints made in this way is such that the head of the valve may be moved about as a whole without any additional clamping mechanism. As the filament and grid can be changed without interfering with these joints, they are of a semi-permanent nature. Only in exceptional circumstances are they ever dismantled.

The anode, D, which is machined from a solid block

of copper, is supported by means of an insulating tube, S_4, directly above the O_3 oil diffusion pump (see Fig. 7D). The two joints are also made using bitumen, and are semi-permanent. The joint normally broken when a filament replacement is made is marked " J." This is remade with either a low melting-point bitumen, which is sufficiently plastic at room temperature to be moulded by hand, or a sealing compound, Apiezon Q, which is a putty-like material. Both compounds have low vapour pressures and may be used up to 50° C.

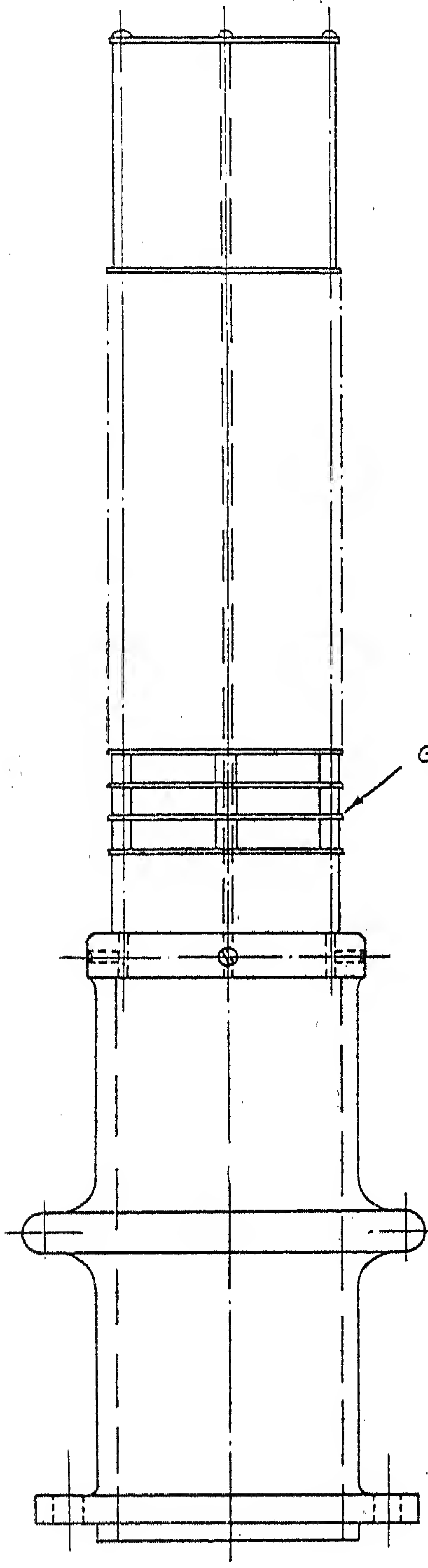


FIG. 7B.—Grid base (the grid).

A series of water-cooling channels are machined in the anode, and so very satisfactory cooling is obtained. In general the valve anode is designed so that it is capable of dissipating the normal input rating of the valve on dead loss without damage to either anode or joints. This is quite a desirable property, since most circuits go into parasitic oscillation occasionally, and when this happens the power taken may be just as high as the normal input under standard oscillatory conditions with negligible output.

Porcelain tubing is used for the insulating spacers for long-wave, and silica tubing for short-wave, valves.

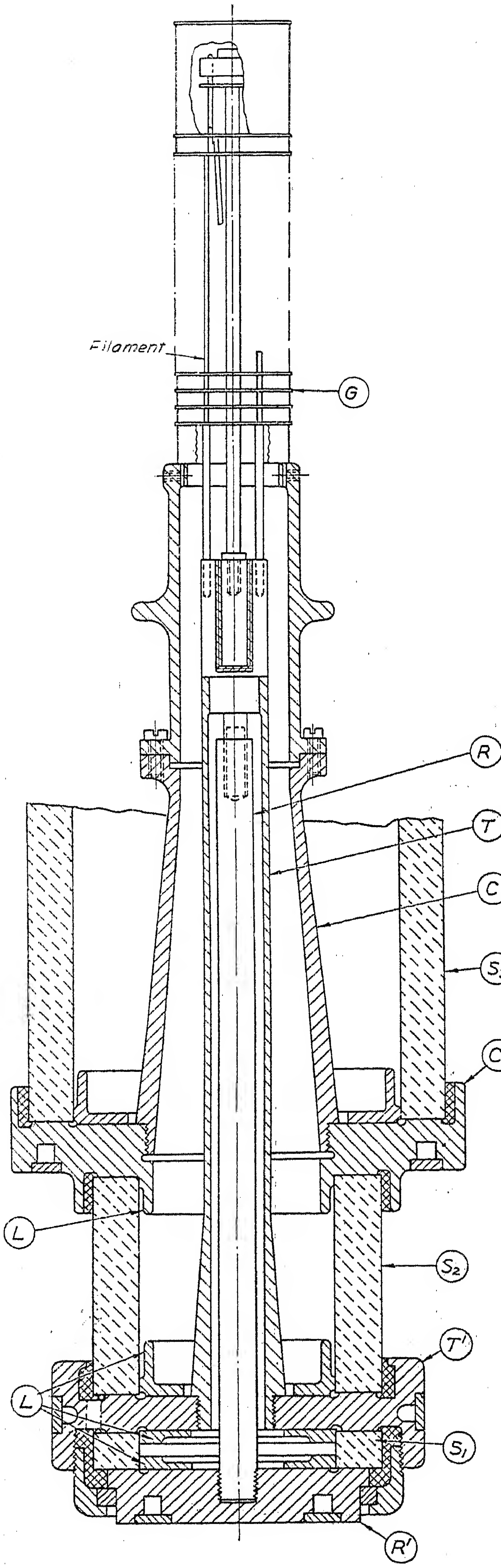


FIG. 7C.—Filament-grid assembly.

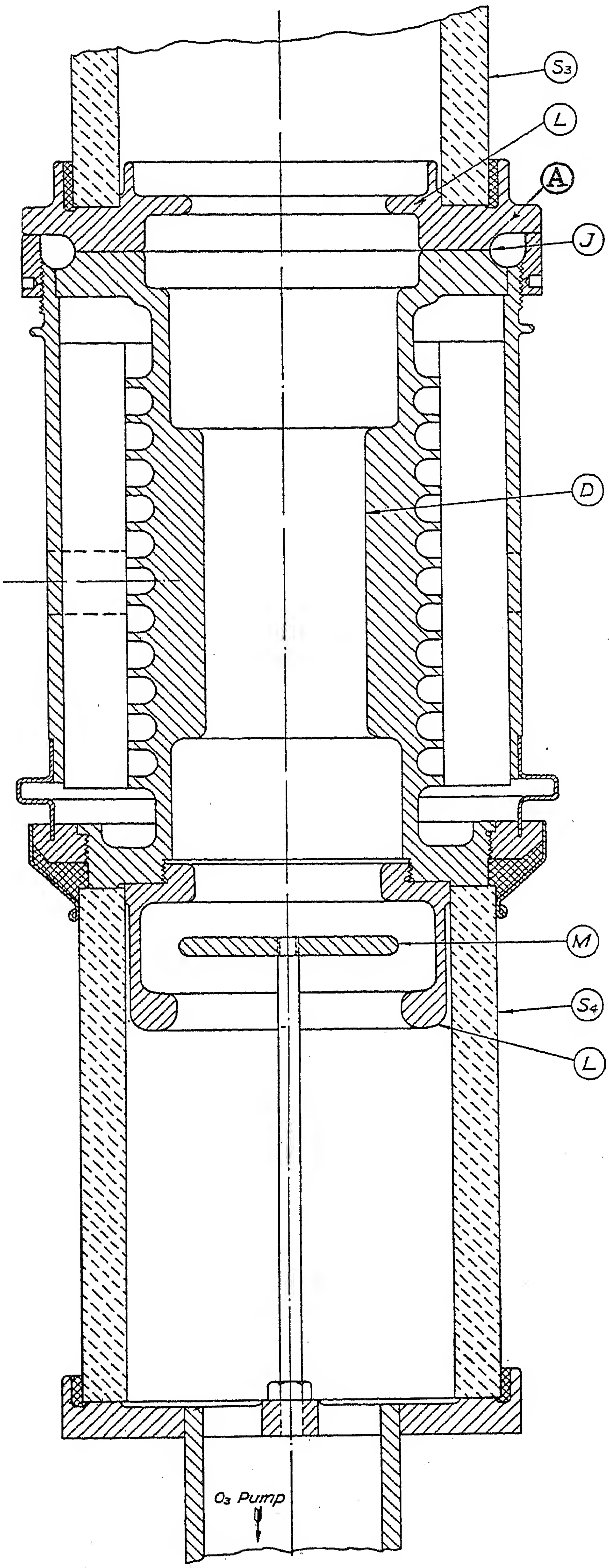


FIG. 7D.—Anode.

The internal edges of the joints between the various insulating tubes and flanges are protected from direct radiation and electron bombardment by means of suitable baffles, L. The grid tube is shaped so that it acts as a baffle so far as the top of the valve is concerned, and in this way the heating of the silica spacers due to radiation from the filament is minimized. At the bottom of the valve, an earthed "mushroom" electrode, M, supported from a flange on the condensation pump, is arranged to form a baffle with the lower end of the anode; this prevents heating of the lower silica spacer. In the event of a flash-arc the mushroom electrode confines the discharge principally to the valve and largely prevents it from entering the pump and decomposing the oil. The baffling system absorbs the soft X-rays produced in the valve.

Apart from the difference in the external form of the valves required in order to simplify assembly, the fact

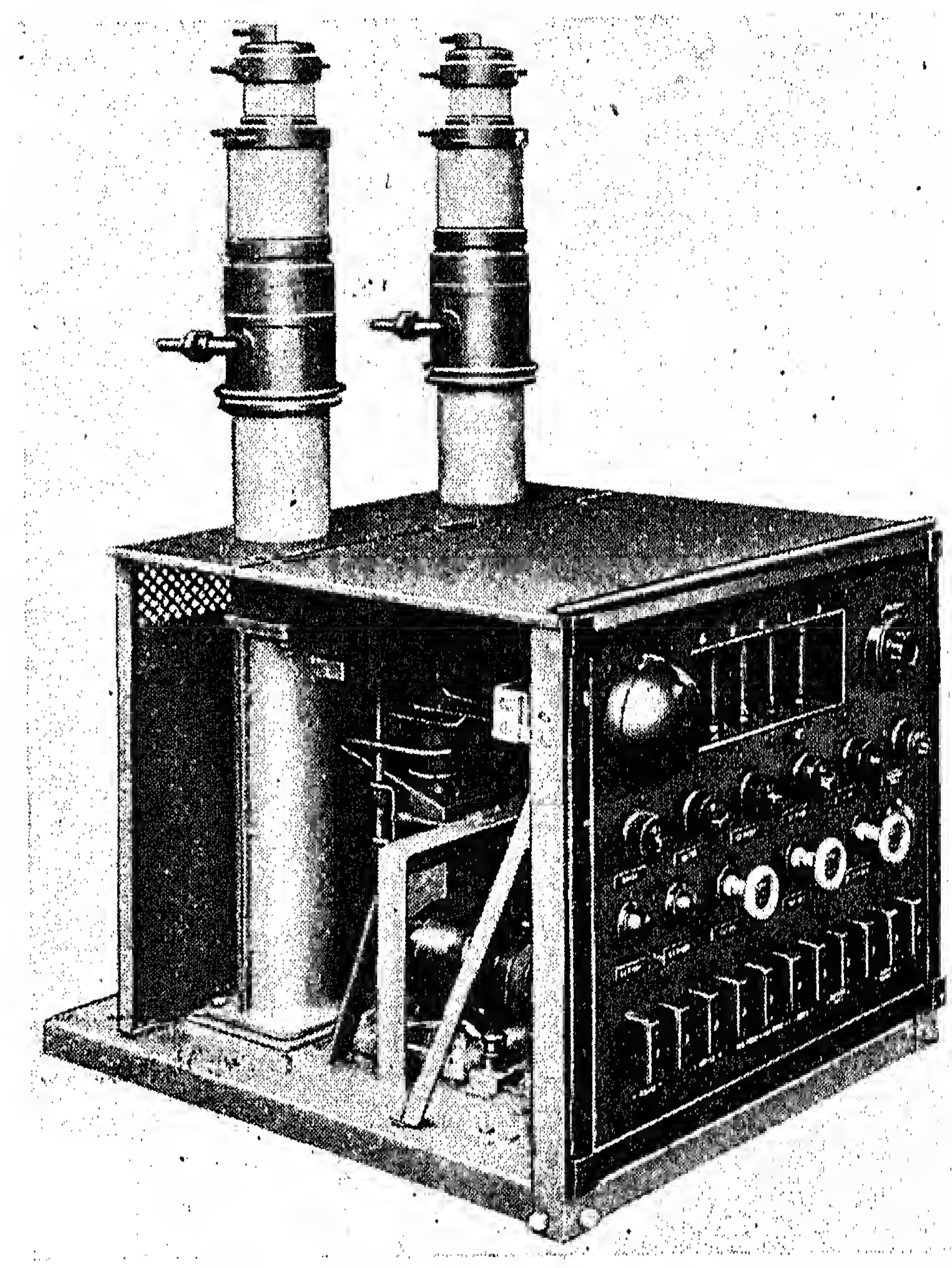


FIG. 8.—Two Type 330 valves on pumping plant.

that the grid and filament structures must be interchangeable calls for a much more robust structure than is normally used in valve design. A specific case, that of the removable filament clamp (see Fig. 7A), may be mentioned. This appears very massive when compared with the usual type of welded structure, but experience has shown that the requisite rigidity and interchangeability are only obtained by such constructions.

Fig. 8 is a photograph of two valves, similar to the one shown in Fig. 7, assembled on their pumping plant.

Fig. 9 is a photograph of a 3-phase 80-kW rectifier for 10 000 volts direct current. The three rectifier valves are all connected to a reservoir which is pumped by a plant similar to that shown in Figs. 4 and 5.

Fig. 10 is a photograph of a cubicle containing a 15-kW 4-electrode valve and its associated oscillatory circuit for a wavelength of 10 m. On the right-hand side is the valve, and on the left-hand side is a con-

tinuously evacuated vacuum condenser which provides the major part of the oscillatory capacitance. Both condenser and valve are evacuated on the same pumping plant. In certain cases the vacuum condenser enables a considerable amount of space to be saved.

(6) Conditioning.

Under normal operating conditions the amount of gas left in a thermionic valve is so small that it plays no appreciable part in the performance of the valve, the current being carried almost entirely by the electrons. If, however, for any reason the gas pressure should rise to 10^{-4} mm or more, the valve will become unstable if

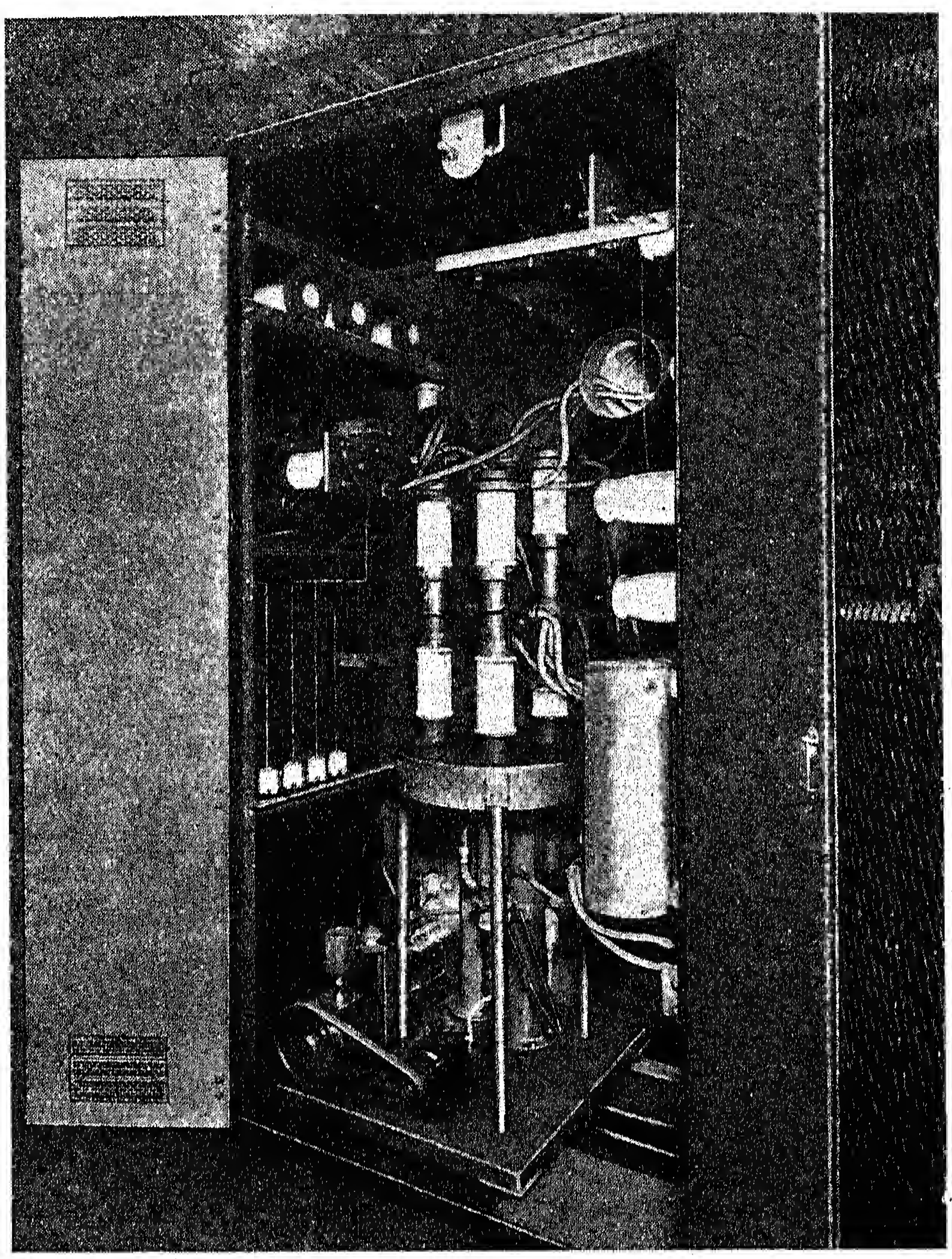


Fig. 9.—80-kW 3-phase rectifier.

working at a d.c. potential of the order of 10 000 volts. At such pressures the number of positive ions produced is sufficiently large to neutralize the space charge at the filament, and a soft arc takes place. In the manufacture of sealed-off valves special precautions are taken to "outgas" thoroughly, before the valve is sealed off from the pumps, those parts which get hot during operation. The grid and anode are heated by electronic bombardment, and the envelope is "ovened" whilst actually connected to the pumps.

In the case of a continuously evacuated valve such thorough outgassing of the electrodes on the pumps is not essential. After manufacture, and before assembly in the valve, the filament is lit to full brilliance *in vacuo.* This removes the oil and grease left by the manufacturing operations. Similarly the grid structure is vacuum-ovened. After this treatment the parts can be stored until required.

Treatment of Electrodes in the Valve.

During assembly of the grid and filament structure a certain amount of grease, moisture, and dust, reaches the active surface of the electrodes. This is removed in the following way. The valve is evacuated, and as soon as the discharge tube on the fore-vacuum shows a green fluorescence the filament is lit. The current is slowly raised until full brilliance is obtained, so that striations do not appear in the discharge tube. This takes about 5 minutes. The grid is then de-gassed by electron bombardment. The power necessary depends, of course, on the size of the grid, and the operation takes 30 minutes. It is not advisable to heat the anode above 80° C., otherwise trouble is encountered owing to softening of jointing material. The de-gassing treatment for the anode aims only to remove absorbed gas from the surface. With grid connected to filament, a d.c. voltage of about 5 000 volts positive is applied to the anode for 5 minutes.

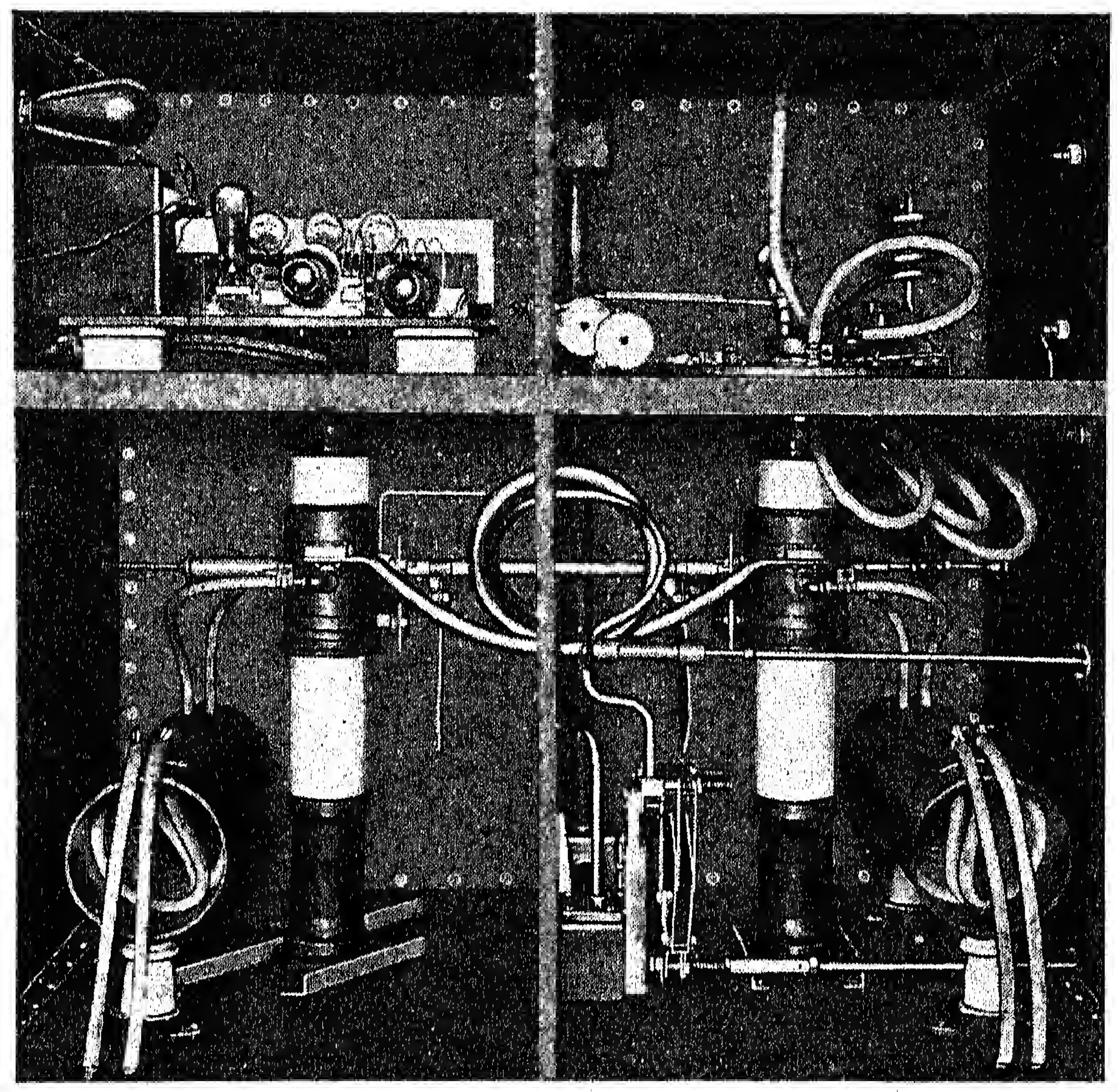


Fig. 10.—Cubicle containing screen-grid valve and condenser.

The above de-gassing processes do not, of course, remove all the gas from the electrodes. Any gas subsequently evolved is continuously removed by the pumps without any noticeable effect on the performance of the valve.

Flash-Arc and Rocky-Point Discharges.

The above de-gassing processes are not sufficient in themselves to render the valve suitable for use on commercial circuits. Thermionic valves exhibit the phenomenon known as the flash-arc. Gossling* defines the effect in the following way: "The 'flash-arc' phenomenon is the spontaneous and complete breakdown of the high insulation normally afforded by a good vacuum between metallic electrodes. The breakdown

* *Journal I.E.E.*, 1932, vol. 71, p. 460.

does not, in general, follow immediately upon the application of the voltage, but is preceded by an interval or 'time-lag' of widely varying duration." Thus a valve which has operated satisfactorily for some considerable time may decide in a very small fraction of a second to offer negligible resistance to the passage of electric current. Unless the supply of energy to the valve is then rapidly restricted or removed, serious damage may result. The precise mechanism responsible for this type of discharge is not known, but it appears to be associated with the condition of the active surface of the electrodes. Gossling has investigated various factors which affect the number and distribution of such discharges for a given electrode system, and has concluded that the number of such discharges per unit time increases very rapidly with increasing voltage and decreases with time at a given voltage, provided the power available during the flash-arc is limited to such an extent that no damage is done to the electrodes by the discharge. The phenomenon appears to be entirely independent of the gas pressure. It has been suggested that the discharges start from minute points on the active surface of the electrodes and that these points are gradually eliminated if the discharges take place under controlled conditions.

Since the tendency to flash-arc decreases with the length of time the voltage is applied, one method of conditioning a valve against this effect is to raise the voltage very slowly and limit the supply so that when a discharge does take place no damage is done to the electrodes. This can be done very easily, for example, by means of a thermionic rectifier which is saturated. The discharges take place at successively higher voltages, and provided the treatment is continued until the breakdown occurs at voltages appreciably higher than the maximum working voltage, the valve can be conditioned in this way. In cases where the d.c. voltage available from the rectifier is not greater than the maximum a.c. voltage on the valve under operating conditions, the valve can be oscillated either on its own circuit or self-excited, using the rectifier as a source of d.c. voltage with very poor regulation.

With other sources of d.c. potential such as mercury-vapour rectifiers or machines which have very good regulation, this method becomes tedious, particularly when all the metallic surfaces in the valve are being conditioned for the first time. Moreover, it is not always convenient in practice to use the normal d.c. operating supply for conditioning purposes, as it may be required for a commercial circuit using spare valves. In view of these considerations the authors have developed a method of conditioning using subsidiary apparatus which is independent of the high d.c. voltage used during normal operation.

High-voltage A.C. Conditioning.

This method makes use of the experimental fact that the higher the voltage the more frequent the flash-arcs, and the sooner, therefore, they are over. With the filament fully bright, the anode is connected to one end of the secondary of a high-voltage transformer, the other end being connected to the filament and earth. The transformer is capable of delivering 100 mA at 40 kV (peak). The voltage on the transformer and negative bias on the grid are arranged so that the current through the valve does not exceed 100 mA. In the primary of the transformer a resistance is inserted, so that the regulation is very poor.

The voltage is raised in stages; at each stage the current through the valve shows a number of flicks (due to flash-arcs), but the regulation is so poor and the voltage on the valve drops so rapidly that the fault is able to heal itself. At any given voltage the flicks rapidly decrease in number, and the voltage is then raised again.

This method is used for two valves in the 60-kW stage of the GBS short-wave transmitter in the Rugby radio station. The peak anode voltage under normal oscillatory conditions is about 18 000 volts; the high-voltage conditioning takes 30 minutes, and consists in raising the a.c. voltage to 30 kV over about 10 minutes, and maintaining it for 10 minutes.

If necessary, an alternating voltage may be applied to the grid during this process and the operation made independent of the normal d.c. supplies. The high-voltage equipment can be mounted on a truck and used for a variety of valves.

After the above a.c. conditioning, the valves are connected in their normal circuits and run up to full load, the voltage being increased in easy stages to the normal operating voltage. Altogether the replacement of filaments in a pair of valves, the evacuation, and conditioning, can be finished comfortably in 6 hours.

The treatment described is adequate for valves in which the electrodes have been newly fitted. No conditioning whatever is required if the valves have been shut down under vacuum, and consequently under normal working conditions no further treatment after the initial one is required. In the few cases where a leak has developed whilst the apparatus has been shut down and the pressure has risen to atmospheric, the authors have found that provided the valves are taken to their normal working voltage in about 15 minutes they give no trouble. In certain circumstances, i.e. grid-filament contact, it is necessary to open up a valve and make a minor adjustment to grid or filament. Provided this is done without touching the active surface of the electrodes, the valve can be reassembled, and, after evacuation, run up to normal operating conditions without any of the special conditioning operations. Such experience indicates that the flash-arc phenomenon is not primarily associated either with the gas pressure or with the adsorbed gas layer on the electrodes. Finally, there have been occasions when valves fitted with entirely new filaments have been put into commission without any special conditioning whatever. This is not, however, the authors' general experience.

Measurements made on various valves operating at 10 000 volts direct current, and used as ionization gauges, show, after conditioning, a backlash ratio of from 10 000:1 to 20 000:1.

(7) Maintenance.

Once the valves have been put into service a certain amount of inspection and maintenance work on joints and pumping equipment is necessary. Occasionally it is

desirable to add sealing compound to a joint or union. The phosphorus pentoxide should be changed as soon as it becomes badly discoloured or wet.

Renewal of the oil in the rotary pump and diffusion pumps is only necessary in the event of an accident involving water getting into the oil. The pump heaters have a safe life of 5 000 hours, and should be changed at the end of this period.

(8) Performance.

The fact that a valve is continuously evacuated cannot be expected to affect its electrical characteristics so far as these are determined by the geometry of the electrodes.

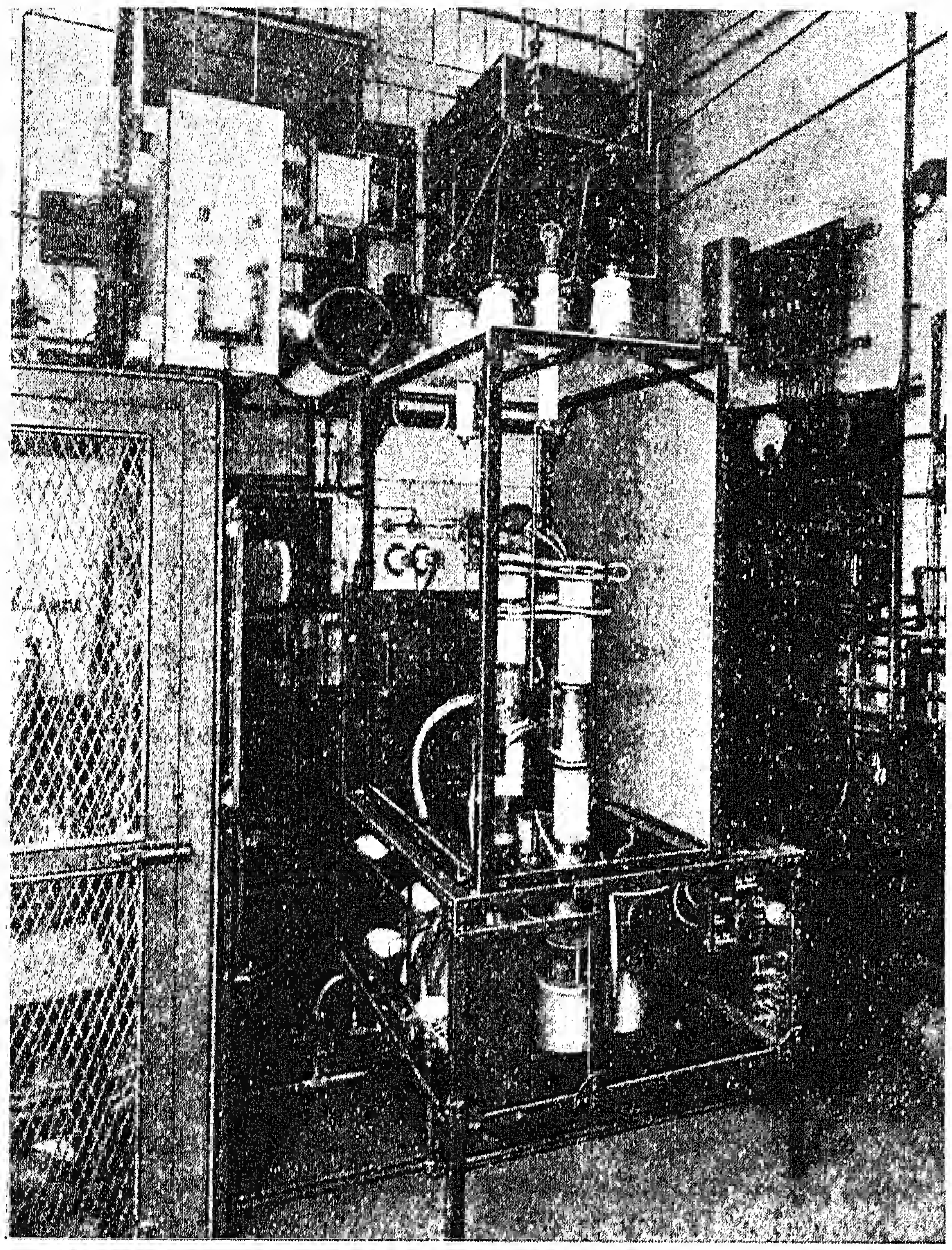


Fig. 11.—Valve cubicle in 10 000-cycle generator.

It might, however, be expected to affect its stability and filament life. Of the valves already made, five have been in service for about 3 years; their behaviour will now be described.

(a) *Two valves operating as a 10 000-cycle generator, used to energize a 20-lb. high-frequency furnace.*—The input to the valves (see Fig. 11) varies from 20 to 45 kW at 12 000 volts direct current, depending on the furnace charge. The power is supplied from a 3-phase thermionic rectifier. The equipment is used about 1 200 hours per year in the routine production of special alloys and hard metal. A filament life of 1 000–1 400 hours is obtained with a filament rating of 600 watts per valve. The grids initially supplied with the valves are still in service.

(b) *One valve used in the GBR 50-kW stage as exciter for the 500-kW stage.*—The frequency is 16 000 cycles per sec., and the valve normally operates with a feed of 0·8 amp. at 7 000 volts. It is fed from a 500-kW d.c. machine through a water resistance of 50 ohms. The filament power is 600 watts. The valve is satisfactory.

(c) *Two valves used in the 60-kW stage of the GBS short-wave transmitter.*—The input to this stage is about 50 kW at 10 000 volts direct current, supplied from a mercury-vapour rectifier through a 50-ohm water resistance. The transmitter normally operates at wavelengths from 16 to 40 m. The filament power is 1·5 kW per valve. No trouble is experienced with the valves once they have been put on to traffic, and no special instructions regarding the rate at which the valves can be brought up to full load are necessary.

As the conditioning process takes such a relatively short time there appeared to be very little point in striving for a long filament life. The authors usually arrange the filament rating so that double the usual thermionic efficiency is obtained, i.e. the saturation current is about 14 amperes per kW of filament power. The information available at the present time indicates that the filament life in continuously evacuated valves is not appreciably different from that obtained in sealed valves under similar running conditions. The ease with which the valves can be assembled and the relative cheapness of filaments produces the possibility that it may be worth while to replace the filament before it has burnt out, and thus eliminate to a very great extent traffic delays due to this cause. This arrangement has now been adopted on the GBS transmitter. The filaments are inspected every 500 hours.

The amount of time lost due to vacuum troubles on the above equipments has been negligible.

(9) Trend of Future Development.

The type of valve described in this paper possesses valuable constructional advantages. It is not readily damaged: for example, the authors have not yet broken a silica pot, and a broken filament or a distorted grid are not costly accidents. Large currents can be passed through the envelope without difficulty; this feature is of particular value in the design of very large valves (500 kW) for long-wave transmission, and in small power valves (30 kW) for short-wave work. With silica as insulator an appreciable amount of power can be generated at wavelengths as low as 5 m. Any breakdown due to electrical discharge or faulty assembly is temporary.

It is true that against the above advantages must be placed the general objection due to the added complication of a pumping equipment. To meet this objection the all-metal pumping equipment has been developed; it is very reliable, and, when fitted with automatic gear, requires very little attention. There is one specific objection which has not been eliminated—about 20 minutes is necessary before the equipment as a whole is working; that is, if started from cold. In a transmitter working 20 hours per day it is customary to leave the pumps running continuously, and in most cases of intermittent working the organization is such that sufficient notice is available. It is, however, conceivable that cases will arise when this delay is objectionable.

The authors have considered the above points in connection with the relative costs of continuously evacuated valves and sealed valves, and have concluded that for valves of 30 kW and upwards there is a definite field for the continuously evacuated type.

With this conclusion in mind the authors started some time ago to develop large valves. There are two possible ways of carrying out such a development: (*a*) to make a series of valves, each one slightly larger than the preceding one; or (*b*) to make immediately the largest valve likely to be required for some time as a single unit. The latter course was adopted when it was decided to construct a 500-kW valve for the long-wave transmitter at Rugby.

The 500-kW Valve.

The general design of this valve has already been described.*

The difficulties normally associated with valves of the 30-kW size in the elimination of flash-arcs are intensified in the 500-kW valve. The active area of the electrodes is proportionally larger, and it is not possible to limit the power available in the case of the discharge to any appreciable extent. The d.c. feed to the valve is normally 50 amperes, so that the use of any appreciable resistance in the anode circuit decreases the efficiency very considerably. Consequently the 500-kW valve has to be conditioned at such a test voltage that under the normal operating conditions the period of flash-arcs is several hundred hours. A satisfactory method of conditioning the valve has now been developed which takes 5 hours. With the present electrode arrangement the valve will take a continuous input of 500 kW at 10 000 volts with reasonable efficiency. It cannot, however, be keyed on the GBR circuit at this input for any length of time. At 300 kW, 7 000 volts direct current, the valve has been operated as a single unit. It has also been used in parallel with a power panel of sealed-off valves to operate the GBR transmitter on normal traffic.

The electrode system is being modified to enable the valve to withstand the keying surge at an input of 500 kW.

Screen-grid Valves.

Another advantage of the type of construction described in this paper lies in the fact that the number of electrodes may be increased almost indefinitely. The advantages of 4-electrode valves for short-wave transmission are fully understood, but until a short time ago no large power valves of this type had been available. The manufacture of two large screen-grid valves, designed and developed by the late Mr. F. P. Burch, has recently been completed. Each valve has taken an input of 60 kW on a wavelength of 10 m. The stability of the valves is exceptionally good, even with a stage gain of from 60 to 80. They are to be used in a short-wave telegraph transmitter at Leafield radio station.

ACKNOWLEDGMENTS.

The investigation described in this paper has resulted from the combined efforts of members of both the technical and the manufacturing sections of the Metropolitan-Vickers Electrical Co., Ltd.

The authors are indebted to the Company for permission to publish this account of the work, and to Mr. A. P. M. Fleming, C.B.E., M.Sc., manager of the research and education departments, for his personal interest and encouragement throughout the course of the investigation. Thanks are also due to the Radio Section of the Post Office, and in particular the staff of the Rugby radio station, for their kind and enthusiastic co-operation.

DISCUSSION BEFORE THE WIRELESS SECTION, 6TH FEBRUARY, 1935.

Mr. A. J. Gill: The authors' attempt to develop from the discovery of their low-vapour-pressure oil a whole range of demountable valves would probably have been very much easier if they had previously constructed cooled-anode valves, and there is no doubt that many of the troubles which they encountered in this work were due to lack of previous experience in that direction. As far as the actual pumping of the valves is concerned, the process seems to be perfectly satisfactory. In some of the earlier experiments the trouble which developed in the pumps was probably due to the quality of the water which was available at Rugby. We found we were trying to run the valves on steam instead of a vacuum, but that was soon cleared up by the use of the cupro-nickel boilers. The 50-kW valves and the two triodes used on short waves with the transmitter at Rugby have been in regular use now for about 2 years. Although the maintenance of demountable valves requires a little more attention than that of sealed-off valves, replacements when they become necessary are very much cheaper.

With regard to the 4-electrode valves, I think the Post Office have helped to stimulate the development in that direction, because we have definite need of a more stable form of valve than the 3-electrode valve for use on transmitters in which the wavelength has to be changed at frequent intervals. We have two of these valves in satisfactory use at Leafield; actually only one valve is operating at a time and the other is a stand-by, so that if any alterations or changes are required the set can be rapidly put into service again on the spare valve. The screen-grid valves do not operate at quite the same ratio of potentials as the ordinary receiving valve. The anode and screen potentials are of the order of 9 000 and 1 500 volts respectively, and that enables us to get a very much greater anode swing without going below the screen potential.

One great advantage of these valves is that, owing to the fact that one can very readily replace the filaments, they can be over-run at times of bad propagation conditions; they have a definite overload capacity, and we feel very secure in the knowledge that if anything goes wrong it can be readily made good.

In the valves which we have had, the grid is composed of a series of washers, and that particular type of grid

* A. S. ANGWIN: *Journal I.E.E.*, 1931, vol. 70, p. 33.

construction has led to rather smaller clearances than usually obtain in 4-electrode valves; I should like to ask whether the authors think that the modified type of grid construction is worth trying for future developments. The present type of grid also seems rather prone to secondary emission. At present on normal heavy-duty rectifiers, in order to avoid damage due to flash-arc which may occur shortly after conditioning, we include a limiting resistance in the high-tension circuit. This reduces the overall efficiency. Do the authors think that the valves can be made sufficiently immune from flash-arcs to allow this resistance to be dispensed with, for example, when we are running with a mercury-arc rectifier with grid control?

I have often wondered whether these flash-arcs are in any way connected with cosmic rays. I believe a somewhat similar device is actually used for counting the cosmic rays; it consists of an evacuated vessel containing two electrodes with a high potential between them, and the cosmic rays apparently cause a discharge across the electrodes. I should like to ask the authors whether they think there is any relation between the flash-arc and cosmic radiation.

Mr. B. S. Gossling: With regard to the upper limit to the "backlash ratio" which the authors mention, we have proved that the existence of this upper limit is not necessarily to be associated with any limit of the pumps or with the existence of irreducible leaks, but may really be due to a quite different defect. The residual "backlash" does not represent an ionic current in the valve, caused by the picking-up of gas ions by the grid; it represents a photo-electric emission of electrons from the grid, excited by the X-rays generated at the surface of the anode by the impinging space current. This matter was studied by a colleague of mine, and a description* of it has been published.

I should like to make some comparison between continuously evacuated valves and existing sealed-valve practice, which has not recently been described. A very considerable amount of high-quality machining is involved in the manufacture of a continuously evacuated valve, and this work seems to be about equal to the corresponding amount of similar work involved in making not only one corresponding sealed valve but the first valve and a whole set of spares. In the larger sizes of valves all this machining work is of a permanent nature and recoverable when the valves are rebuilt, which is not so very difficult a thing to do.

Fig. 7c is extremely reminiscent of the assembly of the inner parts of a sealed valve on the jigs on which it is mounted when the permanent joints are made; this implies that the existence of the permanent joint does not seriously modify the principles on which the valves are assembled.

With regard to flash-arcs, which are still obscure but no longer troublesome, I agree that the mere exposure of the electrode to atmospheric air does not directly favour subsequent flashing. One of my colleagues made some very carefully controlled experiments under severe conditions on that point, and they showed that air can be admitted and pumped out again without causing flashing.

* J. Bell: *Proceedings of the Royal Society*, A, 1933 vol. 141, p. 641.

There is one point with regard to the conditioning work which I should like to mention. The valves have to be run for a considerable length of time on high voltage, and it is apparently customary to have up to 100 milliamps. of space current in the valve, which corresponds to the generation of X-rays in considerable quantity. It is very much a matter of the construction of the valve what proportion of those X-rays get out. I do not suppose much extra provision has to be made in the external insulation of the valve to deal with these extra voltages, and the additional plant would not be expensive.

The sealed valve is surprisingly insensitive to gas evolution after sealing off. It can in fact dispose of a very notable quantity of gas without the pressure rising prohibitively. In practice one can often go considerably over the conservative limit given in the paper of 10^{-4} mm. A certain proportion of the gas molecules are activated in some way and made effectively condensible in suitable parts of the valve where they are not afterwards knocked off again, and they do so condense independently of the free gas, because the molecules do not collide with one another at these pressures. In fact, I would hazard a guess that a sealed valve which had been accidentally softened to a very considerable, though not to a great, extent could be recovered in about the same time by much the same ageing treatment as is described in the paper.

As regards the decision to halve the filament watts, in the smaller valves of about 30 kW this saving seems to be offset to a considerable extent by the total of 900 watts absorbed in the auxiliaries. In sealed-valve practice at the present day the same result has been achieved by doubling the anode voltage, but here there is a point where one must not be misled. Merely doubling the emission by over-burning the filament does not of itself justify halving the anode voltage with a given construction of valve, because at the lower anode voltage to get a similar performance the conductance of the valve has to be multiplied by 4, and for that to be achieved means a complete reconsideration of the geometry of the electrodes and introduces special difficulties. I do not think there would necessarily be any great difficulty in increasing the operating anode voltage of the valves described. A valve which will operate GBR (Rugby) with 10 000 volts will stand 20 000 volts in most other circuits!

I am indebted to the authors for their mention (not in the paper) of the rather mysterious keying surge involving a rise in anode voltage to 26 000 volts. My consideration of flash-arcs at Rugby would have been substantially modified if I had known of such a phenomenon.

With regard to the general life of sealed valves, there are few complaints, and in fact it begins to look as if we were almost within sight of having to consider not only the life of the valves but also the probable life of the station itself. This, however, must be a passing phase.

In the paper it is suggested—and no doubt it would be a very sound procedure—that there should be a regular refitting at stated intervals of the filaments of demountable valves. If this is to be done at stated intervals it will be necessary to consider the statistics

of filament burn-out; it will thus appear at once that the refitting period will have to be one-third, and possibly one-fourth, of the average life to avoid traffic interruptions completely.

The examples given in the paper do not impose any very stringent requirements on the characteristics of the valves. Possibly there is a considerable distance yet to go in meeting those conditions, especially in broadcasting, where extreme fidelity of performance has to be provided. Where we have to deal with refinements of that kind a very suitable way of going to work would be to work out the geometry of any particular type of valve as a demountable valve and then consider whether for large-scale production one would not try to seal it off.

One point which is not mentioned in the paper is the question of duplication of plant for continuous service. The authors say that an immediate change-over to a cold duplicate valve could not be effected, but I expect that problem will be duly dealt with when the case arises. Hitherto there have been sealed valves ready as a stand-by, which would in those conditions have practically an indefinite life and might save the operating staff a night's work at regular intervals.

I rather doubt whether the 30-kW valve is an economic proposition at the present time, except perhaps in special cases. Perhaps there is more to be said for it where two valves are necessarily run together and share a pump. With regard to the 500-kW valve, I think it was an extremely wise decision to introduce this, but on the whole, in view of the considerable progress of sealed valves, it is doubtful whether the 500-kW size is quite large enough. I know that the selection of this size will have been dictated in part by the actual possibilities of operation—an old and great difficulty.

With regard to the fragility of valves, this is a controversy between the installation engineer and the operating engineer. To put it crudely, it is between the man whose idea of a perfect world is one in which he can drop spanners and nuts wherever he likes among the apparatus, and the other who wants to have the kind of apparatus which one can fit and forget. So far as sealed valves are concerned, fragility is not a serious matter. In the hands of people accustomed to handle these valves, accidents rarely happen. The precautions taken in the transport of the larger sealed valves have nothing to do with the glass envelope but refer to the constructional methods used inside to ensure a higher standard of reliability in operation. The protection of the glass by insulator sleeves externally has been discussed on rare occasions, but we have never been asked to adopt it.

In conclusion, I should like to say a word regarding the very "elastic" sympathy provided by the staff of the Post Office Engineering Department. Help of this kind is very freely extended and is doing a great deal to solve a very real problem—the provision of extended trials of high-power apparatus of all kinds.

Mr. H. L. Kirke: The authors make no reference to the grid-filament capacitance and the effect of the rather long leads, which look like a concentric-tube feeder, on very short waves. I should also like to ask them whether they have made any further experiments on waves of less than 10 m. There is very little reference in the paper to secondary emission from the grid, which is one of the difficulties experienced in ordinary valve work. I should also be very interested to know the method of conditioning the 500-kW valve. Also, what is their recent experience in regard to flash-arcs on that valve?

It is our experience that one cannot afford to over-run a valve to any great extent merely by increasing its emission, because the characteristics will not allow of it. The only economy in that direction is the saving of filament power.

Although flash-arcs do not seem to occur as the result of exposing the electrodes of the valve to air, in the paper it is mentioned that care should be taken that none of the electrodes are touched by hand. This seems to be rather an important matter which might be dealt with a little more fully.

Mr. Gossling said that he thought the lives of valves were getting so large now that we had to consider rather the life of the stations. I do not agree with that, but I do agree that the lives of valves are getting extremely good, and I think that is due to the very great co-operation between the users and the manufacturers and to the considerable care which is taken nowadays in the use of valves.

The question of the time taken in changing over from a hot valve to a cold valve prohibits for the moment the use of a demountable or continuously evacuated valve for broadcasting, but it does not do so necessarily in commercial traffic. It is possible to have a delay of a few minutes in traffic, but it is not very popular to have a delay of a few minutes in broadcasting. A point which does not seem to have been touched on very much is the possibility of the use of a demountable type of valve as an experimental valve. If we had had a demountable valve many years ago in the early days of the design of regional transmitters it would have been of great value.

Mr. W. T. Gibson: I tried some of the authors' low-vapour-pressure oil about 1929, and at that time I was not very satisfied with it. It would certainly pump down to a very good vacuum, but with an ionization manometer using combined oxide-coated filament the life of the filament was remarkably short; it became de-activated almost immediately. Since then I have had many further samples of the oil, and there seems to have been a very great improvement. I have had a good deal of experience of the authors' pumps recently, and I can say that without the use of liquid air they will on an ordinary exhausting station give a final vacuum lower than any normally to be obtained with a mercury condensation pump together with liquid oxygen. On the other hand, the fact of de-activation of the ionization manometer still persists, but to a very much smaller extent than before. At the present time with a mercury aspirator together with liquid oxygen one can get a life of 1 000 hours from a manometer opened to air at regular intervals of a few hours, but with oil pumps that life goes down to about 200 hours or perhaps a little less, although the pressure existing in the manometer is lower than it was with mercury. That, however, is not of very great importance when the pump is being used for the exhausting of valves using tungsten filaments.

I consider that the demountable valve may be very

interesting from about 500 kW upwards, but probably not below that figure. One of the points to be considered is that most water-cooled valves are used in broadcasting transmitters. Broadcasting transmitters are often located in the wilds of some foreign country, and the maintenance that is obtainable is not to be compared with that at Rugby or other Post Office stations. It seems to me, therefore, that with the type of joints which are used in this valve the precision of the polished surfaces must be a very important matter; any mishandling may lead to a scratch on one of the surfaces, which probably will then be followed by a leak. This may easily happen unless the station is extremely well controlled. Furthermore, in a transmitter we normally have a group of valves, and the use of continuously evacuated valves would entail a separate pump unit for each one, with its separate control unit and gauges to detect the vacuum and stop the pump if necessary; and water-flow alarms for the pump cooling water. By the time all these necessary precautions have been taken one has a highly complicated piece of apparatus.

In modern broadcasting-station practice it is very common to have a spare valve which can be switched into service immediately. If this spare valve were of the continuously evacuated type we should probably have to wait 20–45 minutes before the valve could be put into service, unless the whole pumping equipment were kept continuously in use for perhaps 10 000 hours, until the moment when it happened to be required. The latter course would put up the general maintenance cost of the station. As a general rule a delay of more than a few moments cannot be allowed in broadcasting practice, and it would be necessary to study the matter in great detail before the demountable valve could be used.

Mr. A. C. Warren: In 1922 I took over the task of developing a continuously evacuated water-cooled valve. Mercury-vapour pumps were employed, but even at that date it was decided to use an all-metal pumping system with oil-sealed taps and conical ground joints both in the pumping system and at the valves. This work had not progressed very far, mainly owing to difficulties in obtaining a vacuum-tight system, when the sealed-off water-cooled valve was produced. The project was then abandoned, the pumps being relegated to the production of receiving valves. I think the most strikingly successful feature of the Metropolitan-Vickers demountable valves is the pumping system and ground joints.

It was early in 1930 that the Metropolitan-Vickers Electrical Co. approached the Post Office with a 10-kW long-wave demountable valve, only to be informed that whilst the Post Office were interested in the demountable proposition they were only interested in long-wave valves of 200 kW and upwards, or in short-wave screen-grid valves of 10–100 kW capacity.

The company courageously undertook both these developments, although their experience of high-power valve design was slight. Before tackling a screen-grid valve, however, they developed a 3-electrode short-wave valve, of the type described in Section 8(*c*). The introduction of the demountable principle involves changes in valve design to facilitate replacement of electrodes, but whilst the authors have rightly tackled the problem from a new angle they have been inclined to adhere to dimensions of the same order as those employed in sealed-off valves. Demountable valves have to be assembled and dismantled by transmitter attendants, who cannot be regarded as valve mechanics. Clearances cannot, therefore, be maintained with the same precision as in sealed-off valves. Yet I believe that in the authors' demountable valves clearances have been restricted to figures even less than in sealed-off valves of the same power and voltage ratings.

Again, one grave source of discharges in valves has been the presence of parts which are not bonded to one or other of the electrodes. In the filament assembly (Fig. 7A) the filament hooks and centre rod are not bonded in this way, and in fact the insulation at the base between the centre rod and the ends of the filament is reduced to a minimum. Attention to these points would, I feel sure, eliminate many discharges which have been experienced in conditioning and in operation.

A sealed-off valve is entirely reliable in operation, does not require skilled attention, can be replaced in a few moments, and can be repaired several times at a fraction of the cost of a new valve. Demountable valves as described in Section 8, (*b*) and (*c*), have been satisfactory in operation, and their cost per kW valve-hour is lower than that of sealed-off valves of similar ratings. They are being operated under particularly favourable conditions, however, since the stages in which they are inserted can readily be replaced by others fitted with sealed-off valves. The demountable valves can then be dismantled, reassembled, and conditioned, at leisure.

For demountable valves to give continuous uninterrupted service two or three valves which can be instantly interchanged are essential, and additional staff may be necessary for their maintenance. These points the authors have realized and have embodied in the design of the screen-grid valves for Leafield radio station.

As a consumer I am naturally biased in favour of the sealed-off valve—leaving the manufacturer to supply a finished and trouble-free article. If, however, the demountable valve can be produced more cheaply and its operating costs—including general maintenance and possible loss of traffic time—are less than those for the sealed-off valve, its widespread adoption for high powers will have to be seriously considered.

At the present time the Post Office are fostering this new development without displacing sealed-off valves, and this state is likely to continue until a reliable comparison can be made.

Mr. H. S. Walker: I shall confine my remarks entirely to that part of the paper which describes the performance of the valves in use.

The details given of the valves in use at Rugby are somewhat meagre. For instance, it would be interesting to know the actual peak voltage. We have heard what the peak voltage is supposed to be at GBR, but we do not know what it is at GBS; nor do we know whether it is modulated or unmodulated. I am surprised that the authors have striven to obtain a filament life of only 1 400 hours as a maximum. If a manufacturer of sealed-off valves were content with this figure, I think the B.B.C. would look elsewhere for their valves. We obtain at the moment an average filament life of well

over 4 000 hours, and there seems to be no excuse for such a short life as 1 400 hours. It requires at least 6 hours (probably much longer) to change the filament, which means extra work for the station staff, who have enough to do already, and I do not see what is gained by putting in new filaments so frequently. It is surely much better to start with a filament which will last for 4 000–5 000 hours. If a valve has to be dismantled for another filament to be put in, there is a chance of one of the seals being damaged in the course of re-assembly. I should be glad if the authors would enlighten us on why they have striven only for such a very short life for the filament.

Mr. J. E. L. Robinson: The authors rather understress than otherwise the advantage of a pumping fluid with permissible vapour pressure at the working temperature. Not only does its adoption remove the nuisance of liquid-air servicing, but by eliminating the necessity for the bulky heat-insulated cooler it immediately renders practical the rigid metal construction of apparatus which the authors employ. This is also facilitated, of course, by the use of the dry-sealed demountable metal-to-metal vacuum joint, of which any necessary number can be fearlessly included without provoking appreciable leakage. In this connection from our own experience we can endorse the authors' preference for the flat type of demountable joint in many instances, the advantage lying not only in their interchangeability but in their manufacturing convenience.

Regarding the vacuum tap described by the authors, I have heard it stated by a responsible member of the firm manufacturing the pumps that the introduction of the standard tap between the units O_2 and O_3 of the pumping set under certain conditions decreases the effective pumping speed by as much as 50 per cent, and of course on maintained pumping this loss is not alleviated by the presence of the reservoir. In this case why is a tap of such small bore employed? Additionally, the tap in question has a rather meandering pumping channel. Have not the authors contemplated the construction of one with a straight-through bore in the open position?

The use of a baffle is described on the O_3 pump; I do not think this baffle is fitted to every O_2 pump, and I would mention that we have noticed traces of what was presumably pump oil deposited on apparatus on the high-vacuum side when it was evacuated by the O_2 pump alone.

The use in the standard vacuum equipment of vacuum gauges and relays at all the vulnerable points is very desirable, but one notices that no mention is made of any calibrated gauge on the high-vacuum side. Such an apparatus, if necessary with detachable filaments, should help to popularize the use of the pumps in circumstances where, as in the authors' case, the possibility of checking the state of the vacuum by the high-voltage characteristics does not obtain. Presumably the delicate nature of the very high-vacuum gauges has been a contributory cause of their omission.

The policy expressed in connection with the rating of valve filaments is interesting. One wonders whether the increased thermionic filament efficiency sponsored is offset by the operating cost of the more frequent filament renewals, or whether any other considerable advantage has been found in the resulting filament construction.

The paper touches the very important question of the cause of flash-arcs. Have the authors any information supporting the view that the effect is mainly related to the adsorbed gas layer on the metals?

Mr. H. Bishop: I should like to have a little more information with regard to the type of seal. The authors mention the use of a flat ground joint; in mercury-arc-rectifier practice other types of joints are frequently used. If the flat type of joint is so good, why has it not been more generally adopted?

I am surprised that the time of conditioning of demountable valves is so small, seeing that the conditioning of other vacuum plants takes a much longer time. If for this type of valve the job is comparatively simple, why is it relatively difficult on similar plants of other types, particularly bearing in mind the stringent requirements of valves as regards the tendency to flash-arc?

Dr. E. H. Rayner: The success of the authors' oil pump is remarkable. It has produced both the demountable valve and the demountable X-ray tube; the latter has made the X-ray tube a piece of engineering apparatus instead of glassblower's art. I believe one or more samples of this type of pump have been made with a cross-section of pipe of the order of 10 000 times what was common a few years ago in ordinary pumping equipment. The pump will provide a new tool for many processes requiring a high vacuum, especially where the high vacuum has to compete with leakage or gaseous evolution. I myself have been interested in attempting to get a very high vacuum in a large piece of apparatus which it is quite impossible to de-gas by thermal methods; we now see our way to a very considerable improvement by making use of one of the large oil pumps devised by the authors. With that piece of apparatus, which is intended to take the form of a high-voltage condenser of several hundred kilovolts for certain precision purposes, we have been troubled with flash-arc discharges. I took the opportunity to try to find out from Dr. Coolidge, when he was over here last, why these discharges happened and how to avoid them; unfortunately he could not do more than give some ideas on the subject of how to avoid the effect. He stated, as has Mr. Gossling, that he did not believe it was due to residual gas.

Turning to the question of cosmic rays, I suggest that at the Rugby station the valve should be put 20–30 ft. underground. It would then be reasonably protected from cosmic rays, and it would only mean a rather longer transmission line for short-wave working. Alternatively, about 3 ft. of lead could be used all round. I am sure the result would be most interesting!

Mr. S. R. Mullard: In the years immediately after the War the vacuum technique for high-power transmitting valves—both of silica and of glass—was still in process of development, and about that time I had an opportunity of following the work done by Mr. Holweck in the Curie laboratories, Paris. Holweck used his molecular pump, and showed that all our difficulties in the extraction of the last traces of gas from the sealed

valve could be avoided by employing his continuously evacuated valve which was also demountable. His difficulties were connected with his pump, which had the rotor very close to the case; this is inevitable with a molecular pump. During prolonged runs, serious breakdowns occurred owing to the overheating of the rotor. The diffusion pump described in the paper seems to have removed all the difficulties which diffusion pumps of other types have carried with them. In my opinion, there should be very little trouble with the vacuum joints.

I still have a sample of a heavy-current focus lamp with a tungsten filament and composition joint produced by Holweck in 1923; I tested the vacuum of the bulb only yesterday and found that it was still in good condition. Apart from the valve, the equipment described by the authors will doubtless have many applications in laboratories and works. I suggest that the pump will have a very big field indeed for laboratory work, as Dr. Rayner has just mentioned.

Mr. C. R. Burch and **Dr. C. Sykes** (*in reply*): Among the many interesting points raised during the discussion there appear to be two main criticisms of the demountable valves described in the paper: (1) short filament life, and (2) the relatively long time—20 minutes—required to start up the pumps on demountable valves.

As stated in the paper, we are of the opinion that a reasonable filament-emission rating for a demountable valve is twice that of a sealed-off valve, namely 12 milliamperes per watt. Under these circumstances an average life of about 2 000 hours can be expected, and the possibility of failure due to filament burn-out under 500 hours is very remote. At the end of this period, which represents about 5–6 weeks' normal running, the filament is inspected. If satisfactory, it is left in and operated for another 500 hours. In this way, it is possible to eliminate traffic shutdowns due to filament troubles almost entirely, and this is the only reason for the periodic inspection.

The choice of average filament life corresponding to that given at twice normal thermionic efficiency was made by us on the following grounds. We considered a 60-kW short-wave transmitter which operated on four 15-kW valves having a filament input of 6 kW. Reducing the filament power to half saves £62 10s. at 1d. per unit in a year of 5 000 hours. During this time there would be on the average 5 traffic delays due to filament burn-out on sealed-off valves. On demountable valves it would be necessary to inspect 10 times, and as a result replace filaments about 5 times. The filament inspections can be made to suit traffic conditions on the transmitter, so that an overall saving of from £40 to £50* can be effected, with a considerable decrease in the number of arbitrary traffic delays. This may not be a large item in transmitter costs; we have no reliable data on this point, but we certainly thought such a saving would be appreciated. On the other hand, if a filament life equal to that of a sealed-off valve is essential, there is no technical difficulty in effecting this.

With regard to the question of spare valves, we have, as stated by Mr. Gill, supplied two demountable valves for the Leafield transmitter; these are mounted on a turntable, so that the spare valve can be put into the traffic cubicle simply by rotating the turntable through 180°. This does not get over the difficulty of the finite time required for the pumps to be put into commission. We are definitely of the opinion that, where such valves are available, sealed-off valves should be used as spares. They would be required to operate whilst the demountable valves were out of commission for inspection purposes. In this way the advantages of the low operating costs of demountable valves would be obtained without the disadvantage of having to operate continuously the pumping equipment of the spare equipment.

We will now reply in sequence to the various special points raised during the discussion.

Dealing first with Mr. Gill's remarks, there appears to be no objection to the use of wire grids, and in many cases they appear to offer advantages over the washer grids. We are of the opinion that with grid control the limiting resistance could be eliminated. The possibility of any relation between cosmic rays and flash-arcs had not occurred to us, and we do not feel competent to give any pronouncement on the subject.

Mr. Gossling's statement regarding the upper limit to the backlash ratio is both interesting and important, and solves a problem which had troubled us for some considerable time.

The conditioning voltage will produce a quantity of fairly soft X-rays, but we are confident that the careful metallic baffling system effectively absorbs it.

With regard to the "mysterious" keying surge on GBR, this has been measured by means of a peak voltmeter and also by means of an oscillograph. It has also been calculated from the constants of the circuit. The values obtained were in satisfactory agreement. It is the normal transient produced on keying by the high-frequency choke and feed condenser, to which every telegraph transmitter is subject.

We can offer no opinion as to whether valves larger than the 500-kW valve are likely to be required; the step from 30 to 500 kW seemed to be adequate at the time.

In reply to Mr. Kirke, difficulties due to leads in a valve are not due solely to capacitance, but to the combination of inductance and capacitance which the electrodes and leads provide; and the concentric system which we have provided, although it has a higher capacitance than the "parallel wire" system of most sealed valves, has a lower inductance, so that when terminated by the electrode capacitance proper, which will be the same in both kinds of valve, it will give a system having a higher natural frequency. In fact, the natural wavelength of the control-grid system on the screen-grid valve is about 1·5 m.

We have carried out a variety of experiments on a transmitter operating on 5 m and have operated valves at 2·7 m with an input of 12 kW. At such frequencies the circulating currents are very high and the type of construction described in the paper permits of the use of electrode connections of adequate cross-section without introducing the difficulty of making permanent glass-to-metal or silica-to-metal seals.

It is not desirable to touch the active parts of valves with the fingers, as traces of grease are usually left behind. This affects the surface, and also gives rise to the evolution of gas during subsequent operation. The

* On a 500-kW telegraph transmitter this amounts to about £450 per annum.

assembly of a valve can be made without such contamination.

We are pleased to hear that the low-pressure oil is now fairly satisfactory for Mr. Gibson's experiments. The improved performance is, however, not due to any change in the oil, as all the samples supplied were from the same batch. There is no doubt, however, that the presence of oil vapour affects oxide-coated filaments whilst it is without appreciable effect on tungsten filaments. In this connection the following calculation may prove instructive. There are about $2 \times 10^{19}p$ molecules per cm^3 at a pressure of p atmospheres. Their mean molecular velocity is 10^4 cm per sec. (molecular weight of oil is, say, 500). Then $2 \times 10^{19} \times 10^4/4p$ molecules will strike each square centimetre per second. The number of oil molecules per cm^2 in a monomolecular layer is not greater than 10^{15}. If then we assume that each oil molecule hitting the filament destroys that part of the emitting surface which it covers, complete destruction of the emission could occur in 200 sec. if the pressure of the oil vapour was 10^{-7} mm. The destruction of emission of oxide-coated filaments in 200 hours, observed by Mr. Gibson, therefore seems hardly surprising.

In practice the sealing compounds are sufficiently viscous to prevent any vacuum troubles such as Mr. Gibson anticipates.

We do not agree with his remarks regarding the duplication of demountable valves. Several valves can be and are operated on one pumping plant quite satisfactorily. Since every valve has its own water supply in any case, one extra water-alarm circuit raises no difficulty.

We thank Mr. Warren for his advice regarding the bonding of filaments, although our experience does not agree with his views on this point. Flash-arcs take place in valves having as filament a single hairpin hanging under its own weight.

We can assure Mr. Walker that 6 hours is quite long enough to cover the time necessary to change the two filaments in a 60-kW short-wave transmitter. The other points have been dealt with earlier in this reply.

In reply to Mr. Robinson, the "responsible member" of our organization was correct in his statement regarding the tap between the O2 and O3 pumps. The "certain conditions" mentioned refer to the pumping system operating with a pressure of 1–10 μ on the fine side of the O3 pump, i.e. when the pumping system throughout is fully loaded. When used for demountable valves, with the exception of a few seconds during the initial pumping from atmosphere, the pressure on the fine side of the O3 pump is about 10^{-5} mm and the speed of the tap does not affect the pumping speed of the O3 pump; it merely raises very slightly the back pressure on the O3 pump. Since this is still very small compared with the ultimate backing pressure of the O3 pump, it is of no importance. In cases where large quantities of gas are continually being passed through the pumps, there are no taps between the O2 and O3 pumps.

We considered the possibility of designing a tap with a straight-through bore, but came to the conclusion that it was too difficult; e.g. if one produces a metal tap similar to the conical glass tap, it is (*a*) very difficult to grind to a satisfactory fit, (*b*) impossible to prevent the oil draining from the bridging grooves while the tap is turned.

The O2 is a backing pump and if used to produce a very high ultimate vacuum should certainly be used with a baffle.

The thermionic valve is itself a very sensitive gauge and under the term "ionization gauge" is largely used in the measurement of high vacua.

Replying to Mr. Bishop, we are surprised to find that flat joints are not used on mercury-arc rectifiers.

We are interested to hear from Mr. Mullard of the nature of the difficulties of the Holweck pump, as we never understood why demountable valve development was not pushed in 1927.

In conclusion, we should like to endorse the remarks made by Mr. Gossling regarding the Post Office Engineering Department, and to express once more our appreciation of the ready and real assistance which they have provided in this development.

INSTITUTION NOTES.

Portrait of Mr. P. F. Rowell.

At a meeting of the Council held on the 16th May, 1935, the President read a letter which he had received from a member suggesting that a portrait of Mr. P. F. Rowell should be issued in the *Journal* to commemorate his completion last year of 25 years as Secretary of the Institution and also the award to him of the Croix d'Officier de la Légion d'Honneur. The proposal was received with acclamation. The portrait forms the frontispiece to this issue.

[F. W. H., *Assistant Secretary, I.E.E.*]

Nominations for Election to the Council.

In addition to those members nominated by the Council (see vol. 76, page 717) the following have been nominated for ballot as Ordinary Members of Council:—

R. BORLASE MATTHEWS (Nominated by J. W. Beauchamp, W. C. Bexon, J. H. C. Brooking, W. B. Esson, W. Fennell, J. J. Fisher, M.Eng., F. T. Hall, B. Handley, T. Stevens, M.E., and Herbert Wilson).

J. H. PARKER (Nominated by E. A. Barker, M.C., W. R. Elliott, E. E. Hoadley, A. J. Hutchinson, A. P. MacAlister, J. Mould, P. E. Rycroft, M.B.E., C. W. Salt, J. E. Tapper, and J. W. J. Townley).

Premiums.

In addition to the Premiums mentioned on page 717 (vol. 76) of the June issue of the *Journal*, the Council have awarded the following Premiums for papers read before the Students' Sections during the session 1934–35:—

Premiums of the value of £10 each:

Author	*Title of Paper*	*Where read*
K. B. BALDWIN	"Power Plant for Automatic Telephone Exchanges"	London
I. B. DAVIDSON, B.Sc.	"The Sealed-off Gas-focused Cathode-Ray Oscillograph"	Sheffield
H. R. NOBLE, B.Eng.	"Gas-filled Relay Applications"	Liverpool
F. G. TYACK	"Street Traffic Signals"	London

Premiums of the value of £5 each:

Author	*Title of Paper*	*Where read*
G. N. COOP	"Some High-Voltage Problems at High Frequencies"	Liverpool
T. E. JACKSON	"The Fuller Use of Telephone Lines in Power Transmission Networks"	Bristol
D. B. MCKENZIE, B.Sc.	"Electrical Equipment of Single-phase Locomotives"	Manchester
D. R. PARSONS	"Short-Wave Radio Communication"	Rugby

Premiums of the value of £5 each—continued.

Author	*Title of Paper*	*Where read*
T. G. PROCTOR	"The Improvement of Load Factor"	Birmingham
J. A. PROWSE	"Public Lighting by Electricity"	Newcastle
P. RICHARDSON	"Stray Losses in Synchronous Electrical Machinery"	Newcastle
I. S. SCOTT-MAXWELL	"Suspension Insulators for E.H.T. Transmission Lines"	Glasgow Edinburgh Dundee

Gaston Planté Medal.

The Société Française des Électriciens has decided, in commemoration last year of the centenary of the birth of Gaston Planté, to institute a silver-gilt Medal, which will be known as the Gaston Planté Medal and will be awarded once every three years for meritorious contributions, either scientific or technical, to the accumulator, primary battery, or electrochemical industry. The first award of the Medal will be made in June 1937, and will be supplemented by a monetary prize of not less than 4 000 francs. There will be no restriction as to the nationality of the recipient.

The electrical engineering Institutions of all countries are invited to submit names for consideration in connection with the award.

In the case of the Institution of Electrical Engineers, candidates should submit their papers to the Secretary of the Institution at least eight months before the award is to be made.

Elections and Transfers.

At the Annual General Meeting held on the 16th May, 1935, the following elections and transfers were effected:

ELECTIONS.

Associate Members.

Adcock, Wilfrid Herbert, B.Sc.
Bailey, Christopher Edmund G., B.A.
Balfre, Philip.
Booth, John Roddy.
Brown, David Gregory, B.Sc.
Buer, Sidney Tredway.
Callison, Thomas Tetlow.
Chew, Samuel Noel.
Coates, Alfred Geoffrey.
Dalzell, Donald Percy, M.A.
Donnellan, Cuthbert, B.Sc.
Erskine, Charles Webster.
Fairthorne, Richard Berkley.
Fleming, William Hamilton D., B.A.
Gibson, William Thomas, O.B.E., M.A., B.Sc.
Graham, Eric Edward.
James, Anthony Samual, M.C.
Lewis, Christopher Leonard.
Ramsbottom, John Scaife.
Simmie, Walter Stewart, B.Sc.
Smith, Fritz Langford, B.Sc., B.E.
Taunton, Harold Roby.
Thompson, Alfred Edward.
Thompson, Harry Francis J.
Thompson, Joseph Henry.
Walmsley, Thomas, Ph.D., B.Sc.
Watson, George Oliphant.

Companion.

Wells, Peter Henry P., B.Sc.

Associates.

Barham, Alfred.
Bostandjis, Harilaos Michael.
Garside, Harold.
Hartley, Herbert Edgar B.
Hazell, Stanley William.
Hunter, John Kenneth, B.Sc.
Morgan, Frank.
Petters, James M'Farquhar.
Rattue, Edward Arthur.
Robson, Frederick George.
Rogans, George.
Thomson, Leonard Philip.
Turnbull, Robert.
Urquhart, Samuel Ramage.

Graduates.

Albuquerque, Albert Marius.
Archer, Frank.
Bakhshi, Narindro Nath, B.A., B.Sc.
Barrie, Hugh.
Black, Joseph Victor McD., B.Sc.
Buick, Robert, B.Sc.
Campbell, Harry.
Cowell, Antony Russell, B.A.
Daruvala, Sorab Ardeshir.
Desai, Shiavax Framroze.
De Silva, Sudharman Ruwanpura.
Dhondy, Rustomji Framji.
Green, Kenneth Reid.
Harris, Arthur Edwards.
Johnston, Andrew Brown, B.Sc.
Kashyap, Basheshar Nath.
Lambrick, George Menzies T.
Mackenzie, Ronald Bain, B.Sc.
Maddison, Walter Hiram, B.Sc.
Manning, Edwin Alexander.
Menon, Kakamamvietil Balakrishna.
Murray, John Bernard, B.Sc.(Eng.).
Neocosmos, John Panagiotis, B.Sc.(Eng.).
Penford, James Edwin, B.Sc.
Price, Trevor Gwyn E., B.A.
Raffael, Alexander Maurice, B.Sc.
Robinson, William, B.Sc. Tech.
Shone, Arthur Brian, B.Eng.
Spark, Henry King.
Timmins, John Henry.

Students.

Armstrong-Lamb, Charles William.
Austin, Frederick Arthur W.
Balazs, Peter.
Bansal, Dev Raj.
Beardmore, Eugene Charles.
Beech, Arthur.
Bishop, Geoffrey Ernest.
Boddington, John.
Bode, Armin Logie.
Coorey, Mututantrige Justin D.
Cow, John Charles.
Crawford, Kenneth Desmond E.
Davies, Harold George V.
Dawson, Keith Campbell.
Duerdoth, Winston Theodore.
Eastwood, William Stuart.
Fichter, John Martin.
Foulkes, Christopher Henry.
Foy, Ernest William H.
Furlong, Henry Donald G.
Griffith, Robert Mervyn.
Hampton, Sidney George.
Hardy, Eric Sidney.
Harper, Samuel Denis.
Harris, Frederick Llewellyn.
Hart, Alfred Stephen.
Hayward, Bernard Thomas
Hill, Constantine Thomas.
Howe, Ronald Lloyd.
Jarman, Frank Edgar.
Jones, Edgar Lionel.
Jones, Frederick Charles.
Kanthawala, Emran.
Kirpalani, Mancho Jeramdas, B.Sc.

Students—continued.

Kumar, Ranjit Chennapragada.
Lal, Banke Behari.
Lal, Chaman.
Lindsay, Kenneth Stewart B., B.Sc.(Eng.).
Livermore, John Edward.
Lowe, Herbert Charles.
McCloghrie, John.
Marshall, Edwin.
Morgan, Richard George W.
Needham, Charles Francis.
Rees, Cyril William.
Riley, Ben.
Shallcross, Strother.
Shepherd, Ronald Bradley.
Shuttleworth, Harry Tootell.
Singh, Agyakar.
Smart, Eric Leonard.
Tayler, Nevil Haig.
Wagstaffe, Horace Walter St. J.
Webster, John.
Whitaker, Leonard William.
Williams, Alfred Henry.
Wright, Leonard Sidney.

TRANSFERS.

Associate Member to Member.

Aston, Kenneth, M.Sc.
Boyton, Robert Alexander S., O.B.E.
Fraser, Herbert Cecil, D.S.O., T.D.
Garner, Richard Hough, M.Sc.Tech.
Julius, Willem Otto.
Shotter, George Frederick.
Smith, Frederick.
Thornton, Norman.

Associate to Associate Member.

Gerrard, Tom.
Goldup, Thomas Edward.
Miller, William Henry.
Smith, Frank Cyril.
Wilde, Charles Clifford.
Winstanley, Samuel.

Graduate to Associate Member.

Ashthana, Rajendra Prasada, M.Sc.
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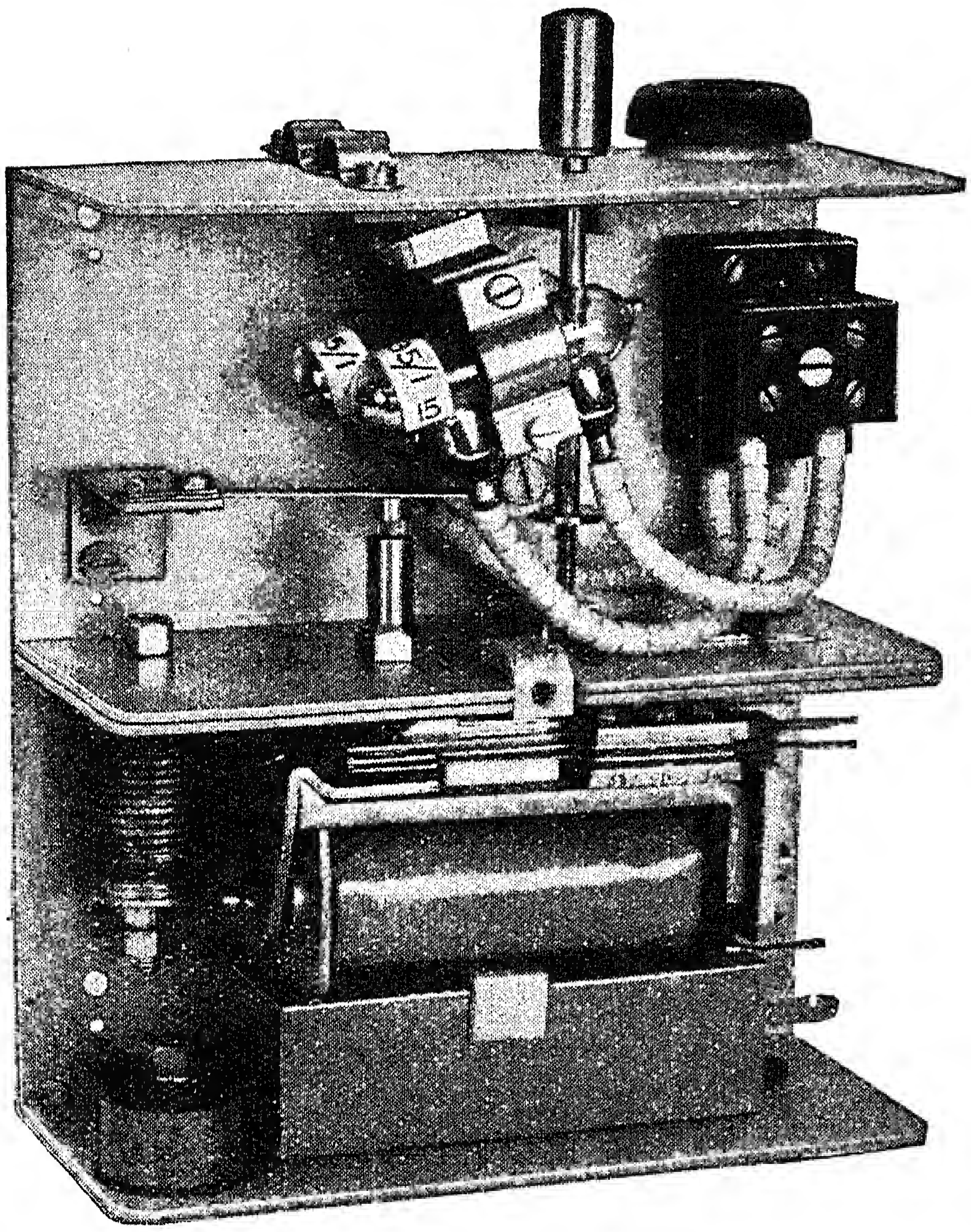

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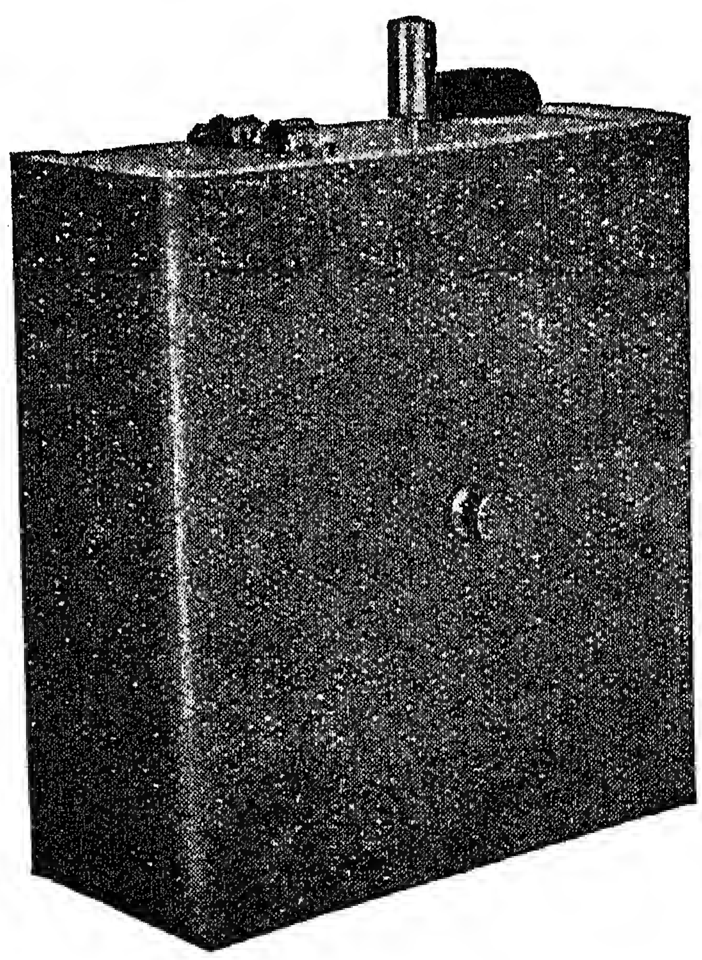

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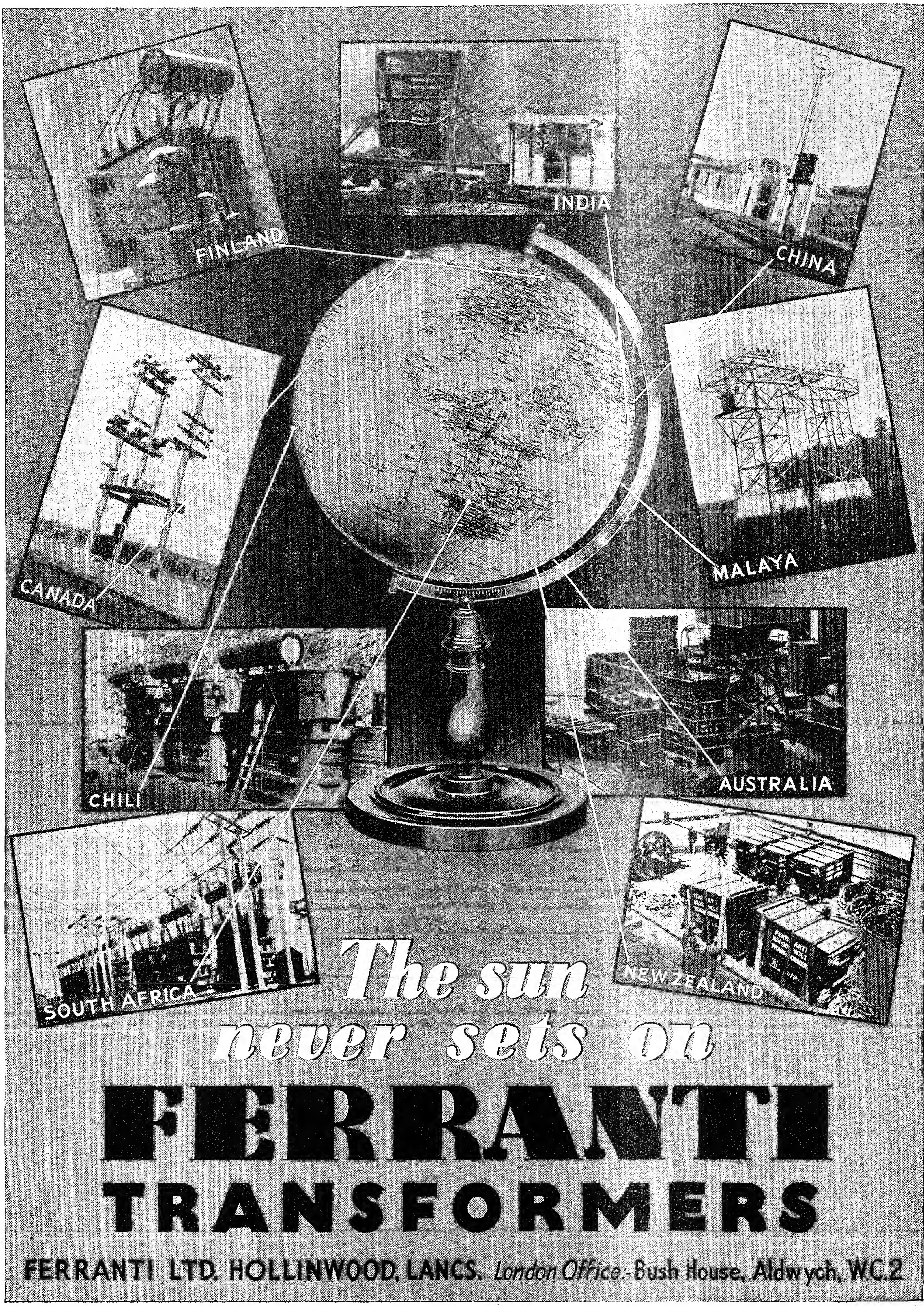

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